Effect of initial stand spacing and breed on dynamic modulus of elasticity of *Pinus radiata*

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Abstract

Wood stiffness or modulus of elasticity (MOE) is one of the most important wood properties for solid timber applications, and as such, the efficacy of wood use, especially for structural timber is strongly related to MOE. MOE in *Pinus radiata* is highly variable and poorly understood. In this study, the effect of initial stand spacing and breed on outerwood MOE and the vertical distribution of MOE of *Pinus radiata* was assessed. Understanding positive or negative influences of growth caused by initial stand spacing and genetic material on MOE is appealing because it could enable us to better comprehend how forest growers could adapt silvicultural operations to the demands of wood processing.

Physical characteristics of different breeds and propagation methods of *Pinus radiata* were assessed at a variety of initial stand spacings. Stem diameter, crown height, stem slenderness and branch size were all heavily influenced by stand spacing. Breed had a marginally significant influence on diameter and stem slenderness. Internode length was not affected by stand spacing, but showed sizeable differences, especially between the long internode 870 breed and the remaining growth and form (GF) breeds.

Outerwood MOE was significantly ($P<0.0001$) influenced by stand spacing and breed, but not their interaction ($P>0.05$). MOE scaled positively with stand spacing. MOE increased by 39% from 5.4 GPa at 209 stems ha^{-1} to 7.5 GPa at 2551 stems ha^{-1}. The majority of this increase (33%) occurred between 209 and 835 stems ha^{-1}. Physiologically aged cuttings of greater maturation status exhibited greater MOE, with the three-year-old cuttings being stiffer than the one-year-old cuttings, seedlings from the 870, 268 and 850 series, by 15, 17, 22 and 27%, respectively. Stem slenderness exhibited the strongest significant ($P<0.0001$) relationship with MOE ($r^2=0.49$), followed by green crown height ($r^2=0.46$) and diameter ($r^2=0.44$). Stem slenderness and green crown height had a direct influence on MOE that explained 53% of the variance in MOE.

MOE was also significantly (P<0.0001) influenced by spacing and breed when using the resonance technique to assess whole stem MOE. The vertical distribution of MOE showed that the lowest portion of the stem (bolt 1) was approximately 30% less stiff than bolts 2 and 3. After the greatest MOE value had been obtained at bolt 3, MOE gently declined to the top of the measured stem. Variation of MOE within trees was significant (58%) at the high stockings of 1457 and 2551 stems ha^{-1}, but somewhat lower (36%) at the lower stockings. The 870 breed was approximately 8% and 16% stiffer than the 268 and 850 breeding series respectively, across all stockings, with the three-year-old cuttings being 7% stiffer than the one-year-old cuttings. At stockings of 481 stems ha^{-1} and less, the proportional height at which MOE was greatest within a tree was between 25% and 50% of stem height. At stockings above 481 stems ha^{-1} the proportional height at which maximum MOE was obtained was between 15% and 40% of stem height. Bolt slenderness was found to be the most significant factor impacting on MOE of the bolt.

Regression of critical buckling height against diameter at ground level yielded a scaling exponent of 0.55, which was lower than the scaling exponent of 0.67 predicted with constant density-specific stiffness. There was a tendency for some bolts with lower mean diameter to display significantly higher safety margins than bolts with higher mean diameter, suggesting that the largest bolts, which occur at the base of tree, are the point of most likely critical failure.

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Table of Contents

List of Tables

List of Figures

Chapter 1

General Introduction

Plantation forests occupy a large area of New Zealand and contribute to a significant proportion of New Zealand's export sector. Export forestry is the third largest export industry in New Zealand, contributing 13% to the total export sector and 3.4% of national GDP. Plantation forests occupy 1.88 million hectares of the 26.9 million hectares of land within New Zealand, of which, *Pinus radiata* occupies 1.63 million hectares or 89% of the total forest resource. Currently, New Zealand's forest industry supplies 1.1% of the world's and 8.8% of Asia Pacific's forest products trade, from 0.05% of the world's forest resource (N.Z.F.O.A., 2005), which illustrates the highly productive nature of the New Zealand forest resource.

Pinus radiata's predominance is attributed to its good growth rates, its broad site requirements, the degree to which growth patterns and stem characteristics can be controlled by tree improvement and forest management, and the versatility of the species for a range of end-uses. The timber can be readily sawn, peeled or converted to pulp (Cown, 1990).

Wood stiffness or longitudinal modulus of elasticity (MOE) is one of the most important wood properties for solid timber applications (Evans and Ilic, 2001). Modulus of elasticity measures the resistance of a material to deflection, with the average MOE of *Pinus radiata* increasing with tree age. This occurs as a result of the MOE increasing rapidly with increasing cambial age or ring number from the pith. Corewood (the inner most cylindrical column of the tree) experiences lower and often unsatisfactory levels of MOE. For several reasons, including faster growth due to better silvicultural and genetic quality, rotations in New Zealand have become shorter, all of which increases the proportion of corewood within a tree thus affecting the quality of the timber produced (Jayawickrama, 2001). Whilst poor intrinsic wood properties found within the corewood zone influence MOE, a recent study has shown that initial stand spacing and genetics have an affect on corewood properties

(Lasserre, 2005). The study described here will examine the MOE of mature outerwood plus that of vertical bolts up the stem. The corewood zone is recognised as liable to be of inferior quality for numerous end-uses, in particular, solid timber applications and is aggravated by a much greater variability that arises from the rapidly changing properties within the corewood itself (Huang *et al.*, 2003). However, if clones are selected for improved stiffness and then coupled with optimal silvicultural strategies for higher stiffness, then stiffness of the corewood region can be increased.

Evaluation of the resource can be made using instruments based on acoustic principles, which are ideal tools for undertaking stiffness measurements as they allow for fast, simple and reliable determination of wood properties (Dickson *et al.*, 2004). Two primary applications are those of "time of flight", which allow for non-destructive sampling and "resonance" methods, which is a destructive method (Andrews, 2000). The use of time of flight methods allows for rapid and non-destructive evaluation of MOE and has the potential to be of great importance to tree breeders for selection of high stiffness clones, to silviculturalists to allow for monitoring of the effect of silviculture on stiffness and to forest owners wanting to select premium stems for the sawmill (Yang and Evans, 2003). The resonance method has been shown to be superior to the non-destructive time of flight method as it provides an estimate of whole log MOE opposed to that of just the outermost few rings of a tree (Andrews, 2002; Lasserre, 2005).

Initial stand spacing can have a major influence on stem characteristics and intrinsic wood properties including MOE (Lasserre, 2005). It is well recognised that lower stocking rates result in numerous undesirable characteristics such as greater branch growth, thus larger knots, and rapid diameter growth and therefore, a higher proportion of less stiff corewood and greater taper. However, the occurrence of these traits at lower stocking rates has not halted the decline in stocking rates over the past few decades. Initial stand spacing may affect MOE in numerous ways. Tree sway, canopy height, radial growth rate and stem slenderness or taper are all possible mechanisms for MOE development, mitigated through stand spacing. By assessing how stand spacing impacts on MOE, and determining how the above factors dictate MOE formation, forest managers will be provided with valuable information allowing

for the determination of optimal initial stand spacing that will allow for greater control of MOE by silviculturalists.

Coupled with stand spacing, another method to improve plantations is genetic improvement. In 1953 an intensive *Pinus radiata* breeding programme commenced with emphasis placed upon improvement in growth rate and stem form. A further breeding programme also started in the late 1960s with selection emphasis placed on longer internodal length to produce an increased proportion of clearwood (Wilson and Carson, 1990). The main breeding effort was established in 1987, in which a rating system was designed to rank seedlots for genetic quality. The rating system is based on growth and form (GF), where a higher improvement rating assures greater genetic improvement (Burdon, 1995). New Zealand's *Pinus radiata* genetic improvement programme has been shown to deliver large gains in traits such as diameter and volume, straightness, log quality and branch cluster frequency (Jayawickrama, 2001). Although it has been found in genetic gain trials that higher GF rated stock has better attributes (Wilson and Carson, 1990), little is known about differences in key wood properties such as stiffness between different genetic materials. Therefore, wood properties have become a major thrust in New Zealand's *Pinus radiata* breeding programme due to a realisation that there will be significant benefits in having improved wood properties in future forests (Sorensson *et al.*, 1997). The present future in genetics of *Pinus radiata* is clonal forestry, which has great potential advantages for increased genetic gains and crop uniformity, but has inherent risks, in that it results in reduced genetic diversity through large scale clonal propagation.

Thesis Objectives

The general objective of this study is to determine the effect of initial spacing and breed on wood stiffness and the vertical distribution of wood stiffness.

More specifically, this study addresses the following objectives:

a) Measure the effect of initial stand spacing and breed on stem size, stem slenderness, branching and internode length of *Pinus radiata* in Canterbury.

b) Determine the effect of initial stand spacing and breed on outerwood and whole stem MOE of *Pinus radiata*, using time of flight and resonance techniques.

c) Determine the distribution of MOE up the stem of *Pinus radiata* at different initial stand spacings.

d) Using measured mechanical properties, determine the critical buckling height and allometric scaling relationships for trees within the experimental plot. Using a variant of the buckling formula, assess the potential of using critical MOE as a predictor of actual MOE.

Experiment Location

The experimental site was located at Burnham, approximately 18 km south-west of Christchurch (latitude 43°36.5'S, longitude 172°17.75'E, altitude 70 m a.s.l.).

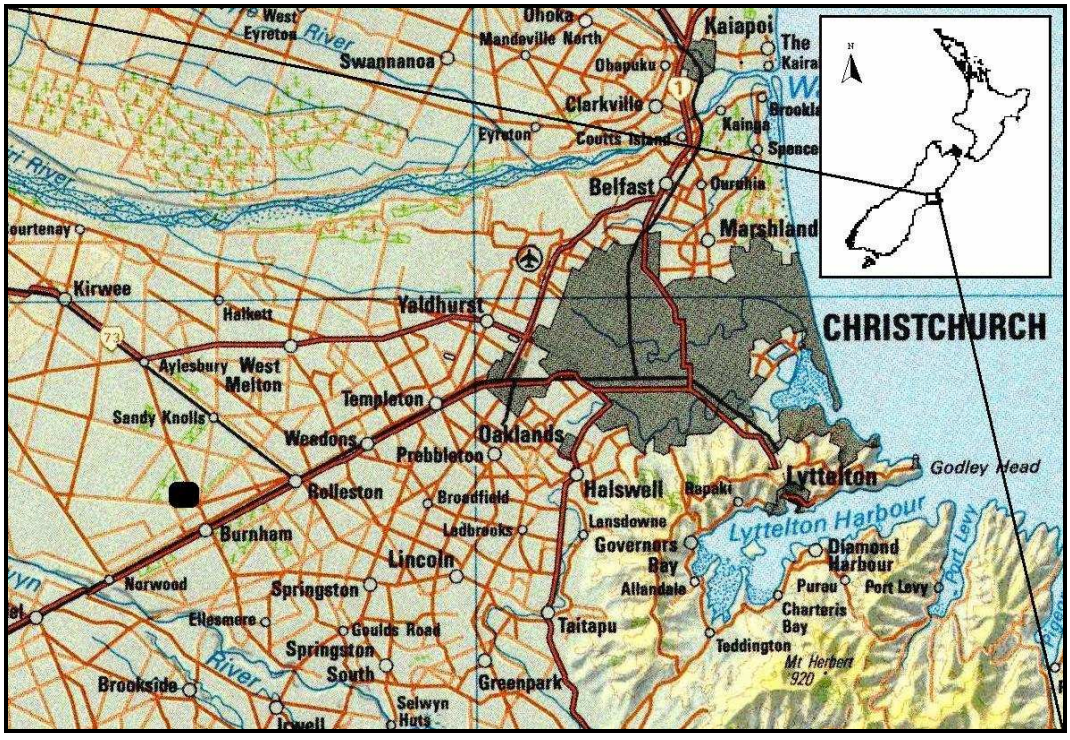

Figure 1.1. Location of experimental plot at Burnham.

Thesis Strategy

This thesis consists of seven chapters. Chapters 1 and 2 provide a general introduction and a review of literature, with particular focus on what MOE is and why it is important, the internal and external factors that influence MOE and methods for assessing MOE.

Chapter 3 examines the effect that initial stand spacing and breed has on a range of physical characteristics of *Pinus radiata* in Canterbury. Physical properties assessed include tree diameter, tree height, crown height, stem slenderness, branch diameter and internode length.

Chapters 4 and 5 assess the effect that initial stand spacing and breed have on MOE of *Pinus radiata*. Outerwood MOE is examined using a time of flight acoustic instrument, whilst whole stem MOE is examined using a resonance instrument. The vertical distribution of MOE is also examined.

Chapter 6 examines critical height and critical MOE. Using measured MOE and wood density, critical buckling height and allometric scaling relationships are assessed for trees within the experimental plot. Critical MOE is determined for outerwood and vertical bolts up the stem and assessed to determine if it can be used as a predictor of actual MOE.

The final chapter (7) presents concluding remarks and suggests further research that could be carried out concerning wood stiffness.

As the chapters contained within this thesis have been written with the intent of publishing them, some paragraphs or expressed ideas will be viewed by the reader on a number of occasions. Although chapters in this thesis examine factors other than MOE, the focus of this thesis is undoubtedly on MOE, thus the fixed attention on MOE in the literature review. No discussion chapter has been included within this thesis as each chapter discusses the results found within.

Chapter 2

Literature Review

General Introduction

Pinus radiata is an exotic conifer introduced into New Zealand from California in the 1860's. *Pinus radiata* is a native species of North America, growing at three locations in coastal Southern California and on two islands off the Pacific coast of Mexico. The species has become a major plantation species in the southern hemisphere where it is cultivated on a commercial scale in New Zealand (1.6 million ha) (N.Z.F.O.A., 2005), Chile (1.6 million ha) [1], Australia (0.74 million ha)[2] and South Africa. It has also been successfully cultivated in Spain, France, Argentina, Greece and India[1].

Pinus radiata is versatile for a range of end-uses owing to its ease of drying, treatability and machinability (Cown, 1990). As a general purpose softwood, *Pinus radiata* can have few equals. Easy to saw, dry, treat with preservatives and machine, *Pinus radiata* is an even textured, medium density, softwood timber which is equally suitable for interior and exterior use, in structural or non-structural applications. It has also proven to be very suitable for the manufacture of plywood, particleboard and fibreboard, and it provides first-class material for both chemical and mechanical pulping. Few other timbers can match *Pinus radiata* for overall performance in such a diverse range of products (Harris, 1991). One of the major products obtained from this species is structural timber, therefore making stiffness or modulus of elasticity (MOE) an important element of wood quality (Jayawickrama, 2001).

Performance and the potential value of products depend on a wide range of interlinked fundamental wood characteristics. These are influenced by the genetics, growth conditions, silviculture, and by the age at which the trees are harvested (Huang *et al.*, 2003). The minimum technical considerations, both for the sawmiller and the consumer, are that the forest products are stiff, and that they remain straight

[1] http://www.greenplan.co.nz/Radiata_Pine.asp
[2] http://www.forests.act.gov.au/radiatapine.html

and stable. Stiffness or the lack of it, is all the more problematic in corewood compared with the outerwood. Consequently, as stands are harvested earlier, the industry has had to face a steady deterioration in wood quality through the increased proportion of corewood, which is further aggravated by a much greater variability that arises from the rapidly changing properties within corewood itself.

Advances in tree breeding and changes in silvicultural practice over the last few decades have greatly enhanced growth rate of plantation grown conifers. These growth gains have resulted in shorter rotation lengths in New Zealand of less than 30 years and therefore, an increased proportion of juvenile wood within the stem. This has caused a reduction in both the strength and stiffness quality of the wood being grown (Booker *et al.*, 2000). Improvements in the overall performance of lumber products, especially stiffness, will depend on knowledge of the most important factors which can be influenced by either silviculture or tree breeding (Cown *et al.*, 1999). Stiffness is a fundamentally important wood property which affects customer perceptions of value in both structural and appearance products, and thus greater controllability of stiffness is required of the sawmilling industry.

Pinus radiata is subject to what has been traditionally called corewood (juvenile wood) and outerwood (mature wood). Whilst these terms are fundamentally flawed, owing to the fact that the terms are seriously inadequate for accommodating the behaviour of some important wood properties and seriously inconsistent with the well-established botanical concept of maturation (Burdon *et al.*, 2004), they are suitable enough when concerned with stiffness and thus are referred to hereafter. The corewood experiences lower density, higher microfibril angles, smaller tracheid length and greater spiral grain than outerwood and as such, stiffness is much lower in the inner rings of the tree than outer rings.

Modulus of elasticity

An important element of wood quality is that of "stiffness" or its modulus of elasticity (MOE). The end-use of wood material, especially for structural timber is strongly related to MOE (Kumar, 2004). However, the low bending stiffness of *Pinus radiata* tends to be a troublesome limitation, especially when the species is grown on the short rotations that are favoured by fertile sites and the silvicultural regimes that are designed for rapid attainment of piece-size specifications (Burdon *et al.*, 2001). The important factors influencing the stiffness of timber are its density and the microfibril angle, but there are many other variables, some anatomical in origin such as knots and spiral grain and some environmental such as moisture content and temperature (Donaldson, 1995; Donaldson and Burdon, 1995; Dinwoodie, 1996; Booker *et al.*, 1997; Huang *et al.*, 2003). Silvicultural practices such as initial stand spacing and the selection of genetic families have also been found to have an influence on MOE (Wang and Ko, 1998; Zhang *et al.*, 2002; Lasserre, 2005).

MOE defines the relationship between stress and strain within the elastic region. Timber is considered to be an orthotropic material with three mutually perpendicular axes in the longitudinal, radial and tangential directions (Xu, 2000). The longitudinal modulus of elasticity is a quantitative measure of the stiffness of the wood along the grain. It is the most commonly measured elastic property and the most important elastic constant. Elasticity implies that deformations produced by low stress are completely recoverable after loads are removed, and this is the accepted criterion of stiffness. The elastic ratios in the radial, tangential and longitudinal directions, as well as elastic constants, vary within species and with moisture content, microfibril angle and basic density (Green *et al.*, 1999).

MOE gradients within *Pinus radiata* trees show apparent radial changes but less conspicuous vertical changes as stated by Tsehaye (1995) and Xu and Walker (2000). Xu and Walker (2000) found in a mill study of 62 trees, that MOE increased radially from the pith to the cabium with the greatest rate of change occurring near the pith. Tsehaye (1995) also reported an increase in stiffness from the pith to the outer part of the log, with the outerwood been almost twice as stiff as that of the corewood. Xu and Walker (2000) found that MOE up the stem showed very little variation and that at

2.4 - 2.7 m up the butt, MOE gradients became cylindrical with no noticeable further decrease in MOE up the tree stem. Similarly, Tsehaye (1995) noted that stiffness changed little in going from the butt log to the top log.

From a mill study, Xu and Walker (2004) concluded that the radial stiffness in *Pinus radiata* logs mimicked that of density, with a very poor corewood and an increasingly stiff outerwood. This trend is also observed in other species such as black spruce (*Picea mariana*) (Zhang *et al.*, 2002) and Japanese larch (*Larix kaempferi*) (Nagao *et al.*, 2000). Dickson *et al.* (2003) found in their study of *Eucalyptus dunnii* that strong correlations existed for density with MOE. Booker *et al.* (1997) in their study of *Pinus radiata* observed that basic density was well correlated with MOE (r^2=0.78). Decreasing microfibril angle was found to have an r^2=0.75 with MOE, whilst decreasing spiral grain had a correlation of r^2=0.25. In assessing the relative importance of density and microfibril angle on MOE, the work by Donaldson (1995) and that of Cown *et al.* (1999) found that when the relationship between MOE, microfibril angle and density were partitioned into juvenile wood and outerwood, microfibril angle was of slightly greater importance than density in the juvenile wood but was significantly less important than density in the outerwood.

Significant differences not only exist for MOE within trees but also have been found between trees. Tsehaye (1995) reported that the stiffest 10% of trees that were examined were almost 80% stiffer than the least stiff 10% of trees that were examined in a study of wood quality. The remaining trees of medium stiffness were 39% stiffer than the least stiff trees. It was also established that in the butt log, the inner half of the log had the lowest MOE of any part of the tree, whilst the outer half of the butt log had some of the highest MOE values for any part of the tree. Xu and Walker (2000) using data from 62 trees which had been cut into 35 x 90 mm lumber and machine stress graded from a 27-year-old stand in the Central North Island, New Zealand, found that by eliminating the least stiff 20% of lumber, the average stiffness of lumber from the remaining logs was enhanced. The difference in stiffness between the two populations was 1.6 GPa.

An area of major concern with regards to stiffness is that of the butt log. The butt log is valuable due to its larger size, higher density and reduced knottiness (if pruned).

However, the butt logs of *Pinus radiata* have a high proportion of low stiffness corewood (Tsehaye, 1995; Xu and Walker, 2000). More significant is that the problems of the butt log are not just limited to the corewood. An enlarged low stiffness wood zone forms a truncated cone from the base of the tree to approximately three metres up the stem, which largely limits the structural use and profitability of butt logs (Xu and Walker, 2000; Huang *et al.*, 2003; Xu *et al.*, 2004). Hirakawa and Fujisawa (1996) found in sugi trees (*Cryptomeria japonica*), that in trees with low stiffness the cone is wider at the base and taller at the apex than in more stiff trees. Perstorper (1996) reported a similar observation in Norway spruce (*Picea abies*), however, only the lowest 1.0 m of the butt log was significantly affected. Xu (2000) found that in the butt log, up to 2.4 - 2.7 m, the average stiffness values are inferior to those found elsewhere in the stem.

It is obvious that a timber property such as stiffness should reflect the increase in density, since density is the measure of the mass of wood substance present in a given volume of timber. However, there is more to it than this. The quality of wood is not necessarily constant, even though the density of wood may be. The stiffness of wood in conjunction with density arises from its cellulose content and the way that it is distributed within the cell wall. Cellulose occurs as very long crystalline microfibrils that are very stiff in the direction of the microfibril axis (Cave and Walker, 1994). All this makes stiffness a difficult property to control and manipulate.

The improvement of stiffness in plantation forests could have a major impact on forest revenue. Dickson and Walker (1997) estimated that a 25 - 50% increase in the MOE of corewood, would result in 50% of corewood been up-graded from low quality uses such as boxing, dunnage or paper, to uses like framing. This would benefit New Zealand growers by $250 million per year.

Internal influences on MOE

Density

Wood density is often considered to be the single most important wood property because of its strong influence on the quality of a wide range of solid wood and fibre products and has as such, received the most attention (Cown *et al.*, 2002). Bunn (1981) states that "basic density is probably the single most important intrinsic wood property for most wood products", while Bamber and Burley (1983) point out, "of all the wood properties, density is the most significant in determining end use". Similarly, Zobel and van Buijtenen (1989) state that "density largely determines the value and utility of wood and overshadows the importance of other wood properties". However, the importance of density as an indicator of wood quality alone is debatable because variability is due to many intrinsic factors, defects and variations inherent in basic wood structure. It is currently considered that density is the most useful characteristic to predict or assess wood quality because it is well correlated with the mechanical properties of wood such as strength and stiffness, yield and quality of pulp and other properties such as machinability, drying rate and acoustic properties (Silcock, 2005).

Tree species have characteristic patterns of density within stems and in *Pinus radiata* the specific values are strongly influenced by a number of factors including tree age, position in the stem, site, environment, genotype and silviculture and is thus subject to much variation (Zobel and van Buijtenen, 1989; Cown, 1999; Cown *et al.*, 2002). Variations in density occur within a stem in both the horizontal and vertical axes. Density is not a simple characteristic but is determined by several characteristics of wood such as cell size and wall thickness, the proportion of major growth ring components (earlywood and latewood), as well as chemical deposits within and between cells (Zobel and van Buijtenen, 1989). Since density is a function of the ratio of cell wall thickness to cell diameter, increasing density results in increasing stiffness of the cell (Silcock, 2005).

Pinus radiata can be described as a medium density softwood with an average basic density of 420 kg m^{-3}. Average wood density increases rapidly over the first 10 to 15 rings from the pith (Xu *et al.*, 2004), rising from around 300 - 320 kg m^{-3} at the pith to between 400 and 500 kg m^{-3} in mature wood depending on rotation age and site. The increase in density with age is thought to be principally due to increases in the proportion of higher density latewood within rings as the tree matures (Cown, 1999). Typically, average earlywood density increases from around 300 - 320 kg m^{-3} at the pith to 350 - 400 kg m^{-3} in "mature wood" – defined as wood further than 10 rings from the pith. On the other hand, average latewood density increases from 420 - 460 kg m^{-3} near the pith to around 450 - 550 kg m^{-3} in the outer rings (Cown *et al.*, 2002). The percentage of latewood within rings typically ranges from 10 - 20% near the pith to 50 - 60% in the outerwood, thus a corresponding increase in average basic density of successive rings particularly over the first 10 or so rings is observed (Cown, 1999). Variations in density between earlywood and latewood may seem large, however, variations found in *Pinus radiata*, are small in comparison with other pines such as the "southern pines or Caribbean pines" and very small in comparison with Douglas fir (*Pseudotsuga menziesii*) (Harris and Cown, 1991).

Cown *et al.* (1991a) reported that the average difference in basic density between the butt logs and the top logs of *Pinus radiata* ranges from 7% to 11%. Cown and McConchie (1982a) in their study of density on samples collected from 10 trees of 12-year-old *Pinus radiata* from Kaingoroa Forest observed a drop in the mean basic density of 50 - 70 kg m^{-3} between the butt and three metres up the stem followed by a decrease of about 10 kg m^{-3} for each further three m height increment to the apex. In further studies, on samples collected from 10 trees of 24-year-old and 10 trees of 34-year-old *Pinus radiata*, Cown and McConchie (1982b) and McConchie and Cown (1984) observed a decrease in the mean basic density of 20 – 30 kg m^{-3} between the butt and breast height and a further 20 – 30 kg m^{-3} decrease for each 10 m height increment to the apex. Tsehaye (1995) observed that butt logs were 6.5% denser than the top logs in his study of 48 trees from a 25-year-old plantation on the Canterbury Plains, whilst Donaldson and Burdon (1995) and Tian *et al.* (1995) also observed decreasing density with height in their study of *Pinus radiata*.

Typically in *Pinus radiata*, stiffness increases by a factor of three to five during the first 30 years of growth. As basic density increases from the core outward, by 30 to 40% over the first 20 to 30 annual growth layers (Tsehaye, 1995), the magnitude of the increase in MOE is far in excess of the increase that could be expected from density alone (Bendtsen and Senft, 1986; Cave and Walker, 1994). Microfibril angle is therefore seen to work in tandem with density to account for the majority of the increase in MOE experienced. Donaldson (1995) found that MOE was significantly correlated with basic density and microfibril angle. Basic density and microfibril angle together explained 80% of the variation in clearwood MOE, whilst Evans and Ilic (2001) found that density and microfibril angle accounted for 96% of the variation in MOE.

Microfibril angle

Microfibril angle is the angle between the helically wound cellulose microfibrils in the middle (S_2) layer of the secondary wall of the tracheid and the longitudinal cell axis (Dadswell and Wardrop, 1959). Microfibrils are long thin filaments of crystalline cellulose and are the main component of the cell walls, making up about 80% of the volume of the middle lamella and form the structural framework of the tracheids, which account for more than 95% of the wood (by volume) (Walker 1993; Dinwoodie, 1996; Pahalawatta, 1999). The microfibrils are surrounded by a matrix of hemicelluloses and lignin. The winding angle of microfibrils in the S_2 layer of cell walls has proved to have a major influence on wood properties, including stiffness, especially in conjunction with density. The performance of wood is closely associated with the microfibrillar angle of the S_2 layer, and it is possible to relate a substantial amount of the variation in strength, stiffness, dimensional instability in the presence of moisture, and fracture morphology to variations in this angle (Dinwoodie, 1996).

Microfibril angle varies within the stem with the highest angles occurring in the corewood – typically in the first 5 – 10 rings from the pith; and small angles occurring in the outerwood, with angles showing a curvilinear decline from pith to bark in *Pinus radiata* (Erickson and Arima, 1974; Bendtsen and Senft, 1986; Donaldson, 1993; Donaldson and Burdon, 1995; Xu *et al.*, 2004). Microfibril angles tend to range

between 10 – 50 degrees within a tree, however, extreme values can be found as high as 70 plus degrees in some trees. Pith to bark trends tend to become flatter with height so that corewood is not as sharply defined beyond seven metres up the stem. Angles may also vary with height and in *Pinus radiata*, shows a rapid decline from the butt to seven metres height at rings of comparable cambial age. Angles then remain more or less constant but may show a slight increase in the corewood of the top log (Donaldson, 1992). Microfibril angles show variation within trees, between trees on the same site and trees in different locations or geographic regions (Donaldson, 1992; Donaldson, 1993).

The changing microfibril angle has a functional purpose in conifer tree growth. It can be assumed that the age dependent decrease in microfibril angle found indicates a functional shift from the flexibility of a young shoot/stem that is required to allow the sapling to bend in high wind without breaking, to the greater rigidity of an older tree stem that must support the increasing weight of the stem and crown (Lindstrom *et al.*, 1998). Modifications of the angle allow branches to maintain their direction of growth and to enable stems forced out of vertical alignment to regain a vertical orientation (Barnett and Bonham, 2004). It is therefore suggested that the microfibril angle of tracheids is a responsive function to vascular cambium activity, turgor pressure and mechanical strains on the tree stem (Lindstrom *et al.*, 1998). Whilst these variations may be of benefit to the tree in order for its survival and continued optimal growth, they can have negative economic consequences for the forest and timber industries.

Walker (1993) stated that microfibril angle in the corewood has an enormous effect on wood properties, and in particular, very strongly determines the stiffness of wood within the first 20 growth rings from the pith, as well as increasing longitudinal shrinkage. Tsehaye *et al.* (1997a) found that decreasing microfibril angle was well correlated with increasing MOE (r^2=0.83). Lindstrom *et al.* (2004) found that microfibril angle had a high correlation with static MOE in three-year-old *Pinus radiata* (r^2=0.75).

A reduction in microfibril angle as distance from the pith increases has been observed in numerous species such as slash pine (*Pinus elliotti*) (Hiller, 1964); loblolly pine (*Pinus taeda*) (Bendtsen and Senft, 1986); cottonwood (*Populus balsamifera*)

(Bendtsen and Senft, 1986); Norway spruce (*Picea abies*) (Saranpaa *et al.*, 1997) and sugi (*Cryptomeria japonica*) (Hirakawa *et al.*, 1997). Walker and Butterfield (1996) have found that the stiffness of cells increase significantly (five-fold) from pith to cambium as the microfibril angle decreases from c. 40 to 10 degrees, whilst Huang *et al.* (2003) state that a three to five-fold increase in stiffness of the cell wall in the axial direction (along the grain) occurs. This occurrence has also been noted in the earlywood of sitka spruce (*Picea sitchensis*), where a six-fold increase in stiffness occurred when microfibril angle decreased from 40 to 10 degrees (Cowdrey and Preston, 1966). Similarly, Bendtsen and Senft (1986) observed a five-fold increase in stiffness over the first 30 growth rings in loblolly pine (*Pinus taeda*). It is dramatic changes in stiffness with decreasing microfibril angle like those examples outlined above that lead Cave and Walker (1994) to state that the measure of cellulose orientation in the S2 layer of the tracheid cell wall is a principle predictor of timber quality, with density behaving as an auxiliary variable. However, since microfibril angle tends to decline sharply with ring number from the pith towards the bark, a corresponding gradient is to be expected in its importance as a determinant of stiffness (Burdon *et al.*, 2001; Evans and Kibblewhite, 2002).

Microfibril angle is known to be inversely related to tracheid length (Donaldson, 1993; Barnett and Jeronimidis, 2004). Because of this correlation, microfibril angle is indicative of cell length and as such gives information on the position of the tree from which the fibres are derived (Dadswell and Wardrop, 1959). The importance of tracheid length was observed by Echols (1955) in slash pine (*Pinus elliottii*) as tracheid length accounted for 91% of the variation in microfibril angle, whilst Erickson and Arima (1974) found that tracheid length accounted for 92% of the variation in Douglas fir.

Tracheid dimensions

Tracheid dimensions are highly correlated with microfibril angle and density. Like microfibril angle and density, tracheid length is subject to considerable variation within and between trees and sites (Cown *et al.*, 1991a).

There is a general trend of increasing tracheid length over the first 15 to 20 annual growth layers. In this region, lengths more than double, from about 1.5 mm close to the pith, to 3.5 - 4.0 mm at the outer growth layers. Though values may increase slightly thereafter with increasing cambial age, there is a tendency for length to fluctuate around a mean value of a little over 4 mm (Bisset *et al.*, 1951; Harris and Cown, 1991). Tracheid length also shows variations between earlywood and latewood of 0.5 mm. The longest tracheids have been found to occur in the outerwood at about 50% of tree height. Tracheid diameter is thicker in earlywood than latewood in both the corewood and outerwood, with diameter been larger in the outerwood. Wall thickness is also greater in the outerwood but is thicker in the latewood than earlywood of both the corewood and outerwood (Harris and Cown, 1991).

There are pronounced regional variations in length, which are weaker than for density, but are well correlated with mean annual temperature (r^2=0.75) and latitude (r^2=0.76). They decrease in length by about 0.75 mm from the north to the south of New Zealand (Cown *et al.*, 1991a).

Within a tree the microfibril angle changes with tracheid length over successive growth layers, the angle being least in the longest tracheids. The variations in microfibril angle that occur within trees and in relation to tracheid length are thought to be controlled by the strains imposed on the cells at their time of differentiation (Donaldson, 1992).

Tsehaye *et al.* (1995) in their study on *Pinus radiata* from Canterbury found that the logs that yielded the stiffest lumber had the longest tracheids. This was also observed in a subsequent study on *Pinus radiata* from Nelson (Tsehaye *et al.*, 1997b).

Spiral grain

Spiral grain refers to the alignment of secondary xylem tracheids at an angle to the stem axis. The cause of spiral grain is not definitely known, but there is evidence that it is a hereditary characteristic of individual trees, and acting through the preferred orientation of the pseudo-transverse tangential division of the cambial initials

(Dinwoodie, 1996). Tian *et al.* (1995) found that 10% of the variation in the MOE of clearwood specimens could be explained by the variations in the angle of spiral grain, whilst Booker *et al.* (1997) found that decreasing spiral grain had a correlation of r^2=0.25 with MOE. This result was also observed by Tsehaye *et al.* (1995). They found that with increasing spiral grain, stiffness decreased in comparison with the stiffness of straight grained specimens. Tsehaye *et al.* (1995) also found that corewood MOE was less sensitive to spiral grain than outerwood MOE, as in corewood, spiral grain has a complementary role to other major factors that result in corewood being of lower stiffness than outerwood.

The greatest angles are usually reached by the completion of the second or third annual growth layer. After this, grain angle decreases slowly and usually approaches zero by the ninth annual growth layer, beyond which small grain angles, seldom exceeding two degrees may occur, thus making spiral grain in *Pinus radiata* essentially a feature of corewood (Harris and Cown, 1991). However, Cown *et al.* (1991b), suggest that spiral grain does not reach the "zero angle" until 15 rings from the pith. Tsehaye (1995) and Cown *et al.* (1991b) have observed when examining *Pinus radiata* samples that spiral grain increases in severity up the stem. They both observed that spiral grain increased significantly up to mid-height of the tree after which, changes were less marked. Tian *et al.* (1995) also noted that the grain increased until a maximum was reached at about 15 metres up the stem, followed by a gradual decrease further up the stem.

Spiral grain has not only been found to influence MOE but be responsible for the higher longitudinal shrinkage observed in juvenile wood (Cown, 1999). Dinwoodie (1996) states that the presence of spiral grain has significant practical implications: twist in dry sawn timber, distortion in plywood sheets, short grained failure of timber under stress and problems during machining.

External influences on MOE

Initial Spacing

Initial spacing can have a major influence on stem characteristics and intrinsic wood properties including MOE, however, the effect of spacing and other influences such as genetics, on wood properties is not fully understood. The effect of spacing on growth and yield, however, is well understood and is an important tool used by silviculturalists. Stocking differences affect wood properties not only through their effect on crown development and growth rate but also through their effect on the utilization of nutrients and water (Zobel and van Buijtenen, 1989).

Past research for numerous species has found that MOE increases with stocking. This is the case for Japanese cedar (*Cryptomeria japonica*) (Wang and Ko, 1998), black spruce (*Picea mariana*) (Zhang *et al.*, 2002) and 11-year-old *Pinus radiata* (Lasserre *et al.*, 2004). Wang *et al.* (2000b) found that for both dynamic and static MOE, lower density stands exhibited a trend toward decreased stress wave and static bending properties. In this study of western hemlock (*Tsuga heterophylla*) and sitka spruce (*Picea sitchensis*), the highest MOE values (stress wave and static bending) were in the control stands or un-thinned stands, followed by those trees in the lightly thinned stands followed by the medium and heavily thinned stands.

Initial spacing is seen to affect the MOE of trees in numerous ways. The proposed mechanisms require further work in order to demonstrate if and to what degree they affect MOE. One proposed mechanism that is influenced by stocking which is an important component of the trees' physical environment is windflow. Reduced stocking allows more wind to penetrate, increases the aerodynamic roughness of the canopy surface and increases turbulence. The trees' crowns are less likely to touch and thus dampen each other's sway (Cremer *et al.*, 1982). The result is increased stem deflection. The effect of low stockings and windflow are varied. It can lead to mechanical stress, which can significantly increase grain angle from vertical to between 5 degrees and 17.5 degrees in *Pinus radiata* (Coutts and Grace, 1995). It also results in increased amounts of compression wood in the stem, which exhibits higher

longitudinal shrinkage than normal wood. The effect of wind also results in increased radial growth and a reduction in stem, branch and leaf elongation (Telewski and Jaffe, 1986). Pruyn *et al.* (2000) found that increased stem movement induced by wind, reduced MOE in *Populus trichocarpa*, whilst Telewski and Jaffe (1986) have stated there is a clear tendency for a decrease in MOE of the stem in response to wind. The effect of spacing on tree sway and its effect on *Pinus radiata* MOE is currently being examined (E. Mason, pers. comm.). The changes in morphology and anatomy produce a tree which is less stiff to counteract excessive stem deflection and possible stem failure. It is also likely that in highly stocked stands, stem slenderness induces high MOE to counteract failure.

Low initial stocking increases radial tree growth, which increases the relative proportion of stem volume occupied by the juvenile corewood which exhibits poor MOE values (Shelbourne, 1997). It is has been proposed that radial growth affects the proportion of anticlinal versus periclinal cell divisions and may therefore affect microfibril angle (J. Walker, pers. comm.). Lindstrom *et al.* (1998) found that the normal trend of pith to bark decrease in microfibril angle can be interrupted by a surge in growth rate such as may occur following thinning or removal of competitor trees. This has led to the suggestion that suppression of juvenile growth could contribute to a reduction in the amount of wood with high microfibril angle in a tree at harvest. Stem slenderness or taper is a further mechanism that theory suggests may regulate MOE. Watt *et al.* (2006a) found that tree taper, which is a function of stocking, accounted for 53% of the variation in MOE for four-year-old *Pinus radiata* across 22 plots established on a range of sites to evaluate site quality. They found that tree diameter and tree height had indirect effects on MOE mediated through taper, however, neither variable had a significant direct influence on MOE. The Euler buckling formula is related to stem slenderness, which suggests that in a competitive situation decreases in taper will induce increases in MOE to reduce the risk of critical failure of the stem.

Canopy height is also seen as an influencing factor on MOE. It is known that green foliage and developing buds produce auxins, and it has been postulated that these auxins influence MOE (Larson, 1962). The canopy rises more rapidly in higher stocked stands and as such lower concentrations of auxins are present in areas below

the green canopy. Auxins play an important part in earlywood/latewood formation, as well as tracheid elongation in conjunction with gibberellin. Current evidence supporting the hypothesis that greater distance from the green canopy results in stiffer wood has come from a School of Forestry (University of Canterbury, New Zealand) experiment (Mason, 2006).

Genetics

New Zealand's *Pinus radiata* breeding programme is reputedly the most advanced in the world (Dorey, 2001) and since 1953 has seen the considerable improvement of many internal and external characteristics. *Pinus radiata* production has traditionally been dominated by a focus on external log specifications such as diameter growth, straightness and forest health (Sorensson *et al.*, 1997). Selections of seedlots in recent times have instead focused on wood quality issues as demonstrated by the development of a 'high density breed' and a 'structural timber breed'. Wood properties have become a major thrust in New Zealand's *Pinus radiata* breeding programmes due to a realisation that there will be significant benefits in having improved wood properties in future forests (Sorensson *et al.*, 1997).

The different genetic breeding series used in this study were all developed to exhibit some traits in a superior manner to other breeding series. Three of the most widely planted series within New Zealand are the 268, 850 and 870 breeding series. The 268 and 850 series are from the same breed. The 870 breed was a first generation special purpose breed. Within the 268 series, one and three-year-old physiologically aged cuttings were developed.

The number "850", "870", "268", is a prefix number denoting a particular series of breed. The first digit in the series number refers to the regional origin of the breed (8 signifies collections carried out by the New Zealand Forest Research Institute, not necessarily within one conservancy, whilst the 2 means that it come from Kaingaroa Forest). The second two digits refer to the year of selection; either 1950, 1970 or 1968 (Vincent and Dunstan, 1989). The 850 and 268 breeding series both have a GF rating. Seedlots of the GF breed cover a range of gain expectations which can be classified

by their GF rating. A relatively unimproved seedlot will have a low GF rating. The rating is an index that allows improvements in growth and form to be combined for ranking the approximate genetic quality of one seedlot versus another (Vincent, 1987).

The 850 breeding series was selected for a combination of the following features: straight stems, light flat angled branching, absence of cones in the lower to mid bole, high vigour and lack of malformation. This series has a GF rating of 14. The 268 breeding series has a GF rating of 22 and comes from the density series. It has a multimodal habit, very good growth and stem form (Jayawickrama *et al.*, 1997a). These GF breeds were devised to be good for structural timber and, when pruned, knot-free timber. However, their selection resulted in the reduction of the average internode length below that of unimproved plantations, which reduces the yield of clearwood in unpruned logs, thus the development of the 870 breed (Jayawickrama *et al.*, 1997b).

The 870 breed is a first generation long internode breed. This breed is designed for longer internodes in an effort to obtain long clear sections from unpruned trees. Carson and Inglis (1988) found the 870 breed had significantly longer mean internode lengths than the 850 and 268 breeding series (Shelbourne *et al.*, 1986). The 870 breed was selected for freedom from malformation, stem straightness, good vigour and uninodal branch habit. However, it tended to show increased malformation, show more susceptibility to top breakage in areas with frequent strong winds such as the Canterbury Plains and have larger diameter branches than GF families (Jayawickrama *et al.*, 1997b).

One (GF 19) and three (GF 17) year-old cuttings were developed from the 268 breeding series. Cuttings provide greater stability at time of planting and in the early years of growth as they have thicker stems and thicker, more stable roots. They also exhibit better stem form (Menzies *et al.*, 2004). However, physiological age should be kept to three years or less if diameter growth losses are to be avoided. Cown (1988) concluded that physiological ageing of seven years or less in cuttings will produce similar properties to those of seedlings. This was also supported by Lausberg *et al.* (1995), who observed few significant differences and no consistent trends.

Tree breeders are currently focussed on stiffness and stability, which are now accepted as the top priorities for breeding solid wood as stated by Sorensson *et al.* (1997) and Jayawickrama *et al.* (1997a). Preliminary studies on small numbers of entries by Matheson *et al.* (1997) and Shelbourne (1997) found high heritabilities for MOE of *Pinus radiata*. Individual-tree heritability estimates for MOE of 0.53 by Kumar *et al.* (2002), compared favourably to those reported by Matheson *et al.* (1997). However, these values are almost double that reported by Kumar (2004) who sampled a greater number of specimens. Given this heritability for MOE, clonal forestry allows for the predictability of such characteristics, which facilities its management and utilisation for particular end-products (Shelbourne, 1997).

Tree-to-tree variation in most wood properties is not only significant but is typically strongly heritable, which makes it easy to improve specific properties by selective breeding. Selection for density, which is highly heritable, is of course an option for indirect improvement of MOE (Burdon *et al.*, 2001).

Cown *et al.* (1992) reported narrow-sense heritabilities of 0.9 - 1.0 for basic density. Burdon (1992) reported a value of 0.7 for narrow-sense heritability of density while Burdon and Low (1992) reported heritabilities for density of 0.73 for two New Zealand land race populations. Lindstrom *et al.* (2004) also found heritability of density to be high (0.78 - 0.90). They also found that spiral grain was heritable (0.55).

Microfibril angle in radiata pine is known to be significantly heritable (h^2=0.7), (Donaldson and Burdon, 1995). Lindstrom *et al.* (2004) found heritability of microfibril angle to be high (0.8 – 0.9) in the lower bolt of three-year-old *Pinus radiata*. Donaldson (1997) stated that the significant genetic component to microfibril angle variability does suggest that some clones have more control over microfibril orientation during wood formation than do others. Donaldson (1995) also has stated that genetic effects can account for up to 70% of between tree variation in microfibril angle within sites. The angle is affected by physiological age, but only within the juvenile wood region, where, generally, average angles are reduced by one degree for every year of physiological ageing.

It would be of considerable interest to both growers and plant breeders whether MOE is influenced by the interaction between initial stand spacing and genetic populations. The absence of such an interaction would mean that plant spacing and genetic populations can be used as complementary approaches for improving MOE (Lasserre, 2005). Previous information examining such interactions is limited as spacing studies tend to exclude genetic populations as a variable, whilst genetic trials use limited spacings to allow for greater and more accurate assessment of the genetic material (Carson *et al.*, 1999). The unique design of a Nelder spacing trial as used in this study allowed interactions between plant spacing and genetic populations to be examined.

Environment

Significant variability in wood properties is a characteristic common to all wood because a tree is subject to many constantly changing influences such as temperature, moisture availability and soil condition. MOE of *Pinus radiata* is perhaps at its lowest in stands situated on dry, stony sites on the Canterbury Plains (Walford, 1985; Tsehaye *et al.*, 1995). This has been shown in machine stress graded tests by Cave and Walker (1994) for MOE in which Canterbury *Pinus radiata* was only 40% as stiff as that from Nelson. Previous work by Walford (1985) from static bending tests has shown that some of the least stiff timber in New Zealand came from the drier, stonier sites on the Canterbury Plains.

The environment has a strong effect on wood density in New Zealand. It has been demonstrated that average annual temperature and rainfall are the dominant climatic influences or latitude and altitude. The environment can influence density as summer drought can reduce the amount of latewood, which reduces wood density in the growth ring, thus impacting on MOE (Cave and Walker, 1994). National wood density surveys have showed that density differences of 25 - 30% occur across the latitudinal range of New Zealand (Cown, 1999; Beets *et al.*, 2001). Overall, mature wood density decreases by seven kg m^{-3} for every one degree increase in latitude and every 100 metre increase in altitude. Most species show variation in wood density across the growth ring which is primarily a response to seasonal climatic variations and the formation of latewood (Walker, 1993). Harris (1965) found that basic density

of the outer ten growth layers at breast height at 37 sites throughout New Zealand, was found to be closely correlated with mean annual temperature (r^2=0.88). Tracheid length was also found to be positively correlated with temperature (r^2=0.56). Cown *et al.* (1991a) found that environmental factors accounted for 61% of the variation in corewood and 66% of the variation in outerwood that they observed.

Beets *et al.* (2001) observed in their study of 27-year-old *Pinus radiata* in Woodhill Forest, north of Auckland, that high cumulative autumn/winter/spring rainfall decreased the latewood percentage and decreased mean wood density, while high summer rainfall appeared to have the opposite effect.

Watt *et al.* (2006a) reported that average minimum temperature accounted for 57% of the variation in MOE for four-year-old *Pinus radiata* across 22 site quality plots, in which the month of March had the strongest relationship with MOE (r^2=0.60). They speculated that the significant influence of temperature on MOE may be mediated through regulation of latewood development. As for March being the most significant month, they state that given that latewood with high MOE is formed during this period, it follows that sites with warmer temperatures and increased growth rates over this month will develop a greater percentage of high MOE latewood and as a consequence higher overall stem MOE.

Methods for assessing the stem

Techniques have been developed that can measure the intrinsic wood quality of logs or trees. These techniques are based on acoustics, which offer one route to determine MOE of wood based on stress wave, ultrasound velocity or sonic resonance (Lindstrom *et al.*, 2002). The most popular techniques used are stress wave or transit time methods, also known as “time of flight” and sonic resonance methods. Both techniques were used in this study. Properly defined and executed, acoustic measurements provide reliable measures of stiffness.

Non-destructive testing techniques are frequently used in the forest products industry using stress waves and have by far received the most attention. Stress wave propagation in wood is a dynamic process that is directly related to the physical and mechanical properties of wood. Examples of the use of stress wave techniques include internal inspections of wooden structures and evaluating internal defects, especially decay in street and specimen trees in public gardens and parks (Divos and Szalai, 2002; Grabianowski, 2003; Wang *et al.*, 2004; Silcock, 2005) and grading of veneer for laminated veneer lumber products (Grabianowski, 2003). In addition to these applications, stress wave techniques can be used to non-destructively evaluate the modulus of elasticity of trees and logs (Arima *et al.*, 1990; Ross and Pellerin, 1991; Booker *et al.*, 1997; Ross *et al.*, 1997; Tsehaye *et al.*, 1997b; Huang, 2000; Wang *et al.*, 2000a; Lindstrom *et al.*, 2002)

The time of flight method measures the time it takes for an introduced stress wave to travel from one point in a sample to another (Lasserre, 2005). It was originally developed to detect rot in trees, not to measure MOE. However, it is the only accurate non-destructive method for measuring MOE in standing trees as no access to the ends of the stem is required. It has been closely correlated to other more precise acoustic methods. However, the method can only estimate MOE within the few outermost growth rings (Andrews, 2000). Huang (2000) concluded in his study of plantation grown loblolly pine (*Pinus taeda*) trees that the velocity of sound wave propagation in the outerwood to be a useful tool for predicting lumber stiffness, whilst Wang *et al.* (2000a) concluded that *in situ* stress wave measurements provide relatively accurate and reliable stress wave information that could be used to assess the mechanical properties of wood in standing trees.

The velocity of sound wave propagation in the outerwood of standing trees is a function of MOE and density (Divos and Szalai, 2002). Stress wave propagation in wood is a dynamic process that is internally related to the physical and mechanical properties of wood. The speed of sound is significantly influenced by the moisture content of the wood because that in turn influences the green density of the tree.

The resonance method is destructive, however, it has been shown to be superior to the time of flight method (Andrews, 2000; Lindstrom *et al.*, 2004; Lasserre, 2005). Here,

the stress wave is introduced at one end of the specimen. It travels down the specimen until it gets reflected. The reflected wave is measured at the same end of the specimen as where the wave was launched. Resonance systems tend to measure the average speed of a number of reverberating waves, rather than the time of arrival of a first wave front. The resonance method has been shown to be sensitive to the presence of bark and branches. Lasserre (2005) noted that when branch and bark removal occurred, an increase in MOE values by an average of 8.3% and 5.4% respectively occurred.

Several studies have found that resonance generated MOE is more closely related to static MOE than time of flight generated MOE. Dickson *et al.* (2004) found a highly significant and positive relationship for acoustic resonance measurements made on logs, whilst a weaker but still significant relationship was obtained for time of flight measurements from standing *Pinus radiata* trees. There was a significant positive relationship between acoustic wave velocity in logs and trees and the timber stiffness. Lindstrom *et al.* (2004) found that resonance and time of flight generated MOE were in close agreement with MOE from traditional static bending (r^2=0.96 and 0.81 respectively), whilst earlier work by Lindstrom *et al.* (2002) found a strong correlation between time of flight measured MOE and static MOE (r^2=0.96).

Numerous studies have shown a good to strong relationship (r^2=0.66 to 0.97) between the dynamic MOE of trees and logs and the static MOE of lumber cut from logs (Arima *et al.*, 1990; Ross and Pellerin, 1991; Booker *et al.*, 1997; Ross *et al.*, 1997; Tsehaye *et al.*, 1997b; Huang, 2000; Wang *et al.*, 2000a; Wang *et al.*, 2001; Lindstrom *et al.*, 2002). Wang *et al.* (2000a) found that the average stress wave velocity measured in trees was very close to that measured in the small, clear specimens, in which statistical analyses indicated no significant difference between the mean stress wave velocity in trees and that in small, clear specimens. The correlation coefficient (r^2=0.83) was highly significant at the 0.01 confidence level, whilst Huang (2000) found that the relationship between stem stress wave velocity and lumber MOE was r^2=0.76. Such relationships between dynamic MOE and static MOE allow for confident estimation of MOE and thus provide silviculturists and geneticist with a valuable tool for the determination of MOE.

Chapter 3

Effect of initial stand spacing and breed on stem size, taper, internode length and branching of *Pinus radiata* in Canterbury

INTRODUCTION

During the establishment of a forest plantation, two of the most important decisions made are the selection of appropriate genetic material and suitable initial stand spacing. Initial spacing can have a major influence on stem characteristics including diameter, taper or stem slenderness, crown height and branch diameter. Differences in stocking affect wood properties not only through their effects on crown development and growth rate but also through their impacts on the utilization of nutrients and water (Zobel and van Buijtenen, 1989). As with initial spacing, tree breed can influence internal and external characteristics in varying ways depending on what trait or traits that genetic material was selected to exhibit. Whilst considerable research has focussed on how genetic material and initial stand spacing impact on the external characteristics of growth and form (Fries, 1984; Carson *et al.*, 1999; Land *et al.*, 2003), apparently no reported studies have examined the interaction of these factors on *Pinus radiata*, incorporating such variation in stand spacing and genetic material as that used in this trial.

Tree morphology is markedly affected by intra-specific competition. Intra-specific competition is a function of initial stand spacing and the growth rate of the trees, and thus begins earlier at high initial stockings than at low ones. When competition between trees reaches a certain point, self-pruning causes the live crown to recede, which is commonly attributed to the earlier death of lower limbs due to shading, with trees in stands of low stocking retaining live branches in their bases longer than trees growing in dense stands. This in turn influences diameter, stem slenderness and branch size. Under the crown competition of a dense stand, branching variability is less, and less foliage is carried on a per tree basis. Radial growth is markedly responsive to spacing, with larger diameters occurring at wider spacings, with growth

under high stand stockings less in absolute terms, but latewood production being greater in proportional terms (Lanner, 1985; Ballard and Long, 1988). Cromer and Pawsey (1957) found that a linear relationship existed between mean diameter and spacing, whilst Sjolte-Jorgensen (1967) found that the mean diameter of trees in a stand increased with increasing spacing.

Tree height appears to be relatively unaffected by stand spacing, except in extreme situations. It has been asserted on numerous occasions that stocking has no significant impact on height growth. Hocker (1979) stated that "height growth is not too greatly affected by stand density…except that height growth may be affected where the stands are near the extremes of stocking". Lanner (1985) states that "it is almost axiomatic that height growth of canopy trees is insensitive to initial spacing and to the changes in spacing that follow the thinning of stands", whilst Cremer *et al.* (1982) and Siemon *et al.* (1976) noted that stocking of *Pinus radiata* had little or no influence on tree height. However, in a review of experiments by Sjolte-Jorgensen (1967), it was found that in most cases for conifers, the mean height of the stand is increased with increasing stocking. This observation of increasing height has also been noted by Mason (1992), Maclaren *et al.* (1995) and Carson *et al.* (1999).

Stem slenderness is markedly affected by spacing, as it increases as stand stocking increases. This is primarily due to the ratio of height to diameter growth experienced by the tree. Secondary to this, stem slenderness is affected as the distance between the live crown and the base of the stem increases, with proportionately more growth occurring at the top of the first log than at the base thus reducing taper of the log (Larson, 1969). This radial expansion of the stem has been observed to occur below an application point of auxin (Sundberg *et al.*, 2000), an important growth hormone, which explains why the maximum radial growth occurs in the general vicinity of the live crown base, which results in small crowned trees been more cylindrical as opposed to the strongly tapered stems of trees with long, vigorous crowns (Larson, 1962).

Branch size is heavily influenced by stocking, and is recognised to be a vital factor in assessing quality and value of timber. It is measured using branch index (BIX)[3]. BIX has a major impact on the recovery of structural timber grades and as such, is an important external property that declines when stocking increases. Larger knots produced as a result of increased BIX have been acknowledged to be responsible for stiffness reduction, especially in structural timber and are therefore undesirable features (Xu, 2002). Tombleson *et al.* (1991) found that branch index for the second log of *Pinus radiata* decreased with increasing stocking. However, they observed that there was no obvious trend with stocking for internode length, which has also been noted by Siemon *et al.* (1976) and Grace and Carson (1993). Ballard and Long (1988) also found that branch size was strongly influenced by stand spacing, whilst Cromer and Pawsey (1957) found in their study of *Pinus radiata* that a linear relationship between average branch size and initial stocking existed.

New Zealand has a longstanding genetic improvement program for *Pinus radiata*, which has seen breeders been proactive in trying to improve external and internal characteristics of *Pinus radiata*. The breeding program has been described in numerous publications (e.g. Shelbourne *et al.*, 1986; Jayawickrama *et al.*, 1997a). The breeding programme has produced planting stock with altered external features such as internode length and branch diameter. Three of the most widely planted series within New Zealand are the 268, 850 and 870 breeding series. The 268 and 850 series are from the same breed. The 870 breed was a first generation special purpose breed selected for long internodes. Within the 268 series, one and three-year-old physiologically aged cuttings were developed. A brief description of traits and origins of the breeds is given to provide background on the material on which this study was carried out on.

The number “850”, “870” and “268” is a prefix number denoting a particular series of breed. The first digit in the series number refers to the regional origin of the breeding series (8 signifies collections carried out by the New Zealand Forest Research Institute, not necessarily within one conservancy, whilst the 2 means that it come from the Rotorua district). The second digit refers to the year of selection; either 1950,

[3] BIX is the mean of the largest branch in each of the four quadrants for the nominated log length.

1970 or 1968 (Vincent and Dunstan, 1989). The 850 and 268 breeding series both have a growth and form (GF) rating. Seedlots of the GF breed cover a range of gain expectations which can be classified by their GF rating. A relatively unimproved seedlot will have a low GF rating. The rating is an index that allows improvements in growth and form to be combined for ranking the approximate genetic quality of one seedlot versus another (Vincent, 1987).

The 850 breeding series was selected for a combination of the following features: straight stems, light flat angled branching, absence of cones in the lower to mid bole, high vigour and lack of malformation and has a GF rating of 14. The 268 breeding series was selected for fast diameter growth, good stem form and multinodal branch habit with evenly distributed branch clusters, with the seedlings, one-year-old cuttings and three-year-old cuttings from the 268 series having GF ratings of 22, 19 and 17, respectively. (Shelbourne *et al.*, 1986). These GF breeds were devised to be good for structural timber and when pruned, knot-free timber. However, their selection resulted in the reduction of the average internode length below that of unimproved plantations, which lead to the development of the 870 breed (Jayawickrama *et al.*, 1997b).

The one (GF 19) and three (GF 17) year-old cuttings come from the 268 series but different seedlots. Cuttings have been found to provide greater stability at time of planting and in the early years of growth as they have thicker stems and thicker, more stable roots. They also exhibited better stem form and less malformation (Menzies *et al.*, 2004). However, it is recommended to confine physiological age of planting stock to three years or less if diameter growth losses are to be avoided. Cown (1988) concluded that physiological ageing of seven years or less in cuttings will produce intrinsic wood properties similar to those of seedlings. This was also supported by Lausberg *et al.* (1995), who observed few significant differences and no consistent trends in younger physiologically aged cuttings.

On an individual tree, internode length is under strong genetic control. Tree breeders have taken advantage of this fact in developing a special purpose “long internode” breed (Grace and Carson, 1993). The 870 breed is the first generation long internode breed. It is designed for longer internodes in an effort to obtain long clear sections from unpruned trees. Carson and Inglis (1988) found that the 870 breed had

significantly longer mean internode lengths than the 850 and 268 breeding series. The 870 breed was selected for freedom from malformation, stem straightness, good vigour and uninodal branch habit and come from a much narrower genetic base than both the 850 and 268 series. It however, tended to show increased malformation, show more susceptibility to top breakage in areas with frequent strong winds such as the Canterbury Plains and have larger diameter branches than GF breeds (Jayawickrama *et al.*, 1997b).

The objective of this study was to examine the influence of initial stand spacing and breed on stem and branch characteristics of *Pinus radiata*, identifying where significant interactions between breed and stocking exist. The wide range of stand spacings coupled with the three breeding series, two propagation methods and different maturation status of the cuttings allowed for a thorough examination of the effects these factors have on stem geometry of *Pinus radiata* on a dryland site.

MATERIALS AND METHODS

Location

Measurements were taken from 17-year-old *Pinus radiata* trees that had been grown in a Nelder experiment (Nelder, 1962) located at Burnham, approximately 18 km south-west of Christchurch (latitude 43°36.5'S, longitude 172°17.75'E, altitude 70 m a.s.l.). The trial was situated on Lismore stony silt loam soil (N.Z.S.B., 1968) and experienced a mean annual precipitation of 650 mm, in which seasonal water deficits do occur during January to March, when evapotranspiration exceeds rainfall (G. Furniss, pers. comm.).

Experimental Plot

The experiment comprised five breed/cutting treatments, including seedlings from the 850, 870, and 268 breeding series and cuttings taken from one-year-old and three-year-old parents. Both the one and three-year-old cuttings were from the 268 series. The Nelder contained 45 spokes separated by 8 degree intervals in 10 circular rings (Figure 3.1) with high initial stocking rates present at the centre of the Nelder to low initial stocking rates present on the outer ring of the Nelder (Table 3.1). Each breed/cutting treatment occupied nine of the spokes split in a group of five spokes on one side of the plot and a group of four spokes on the other side of the plot.

Table 3.1. Nelder design.

Circle number	Radii of planting circles(m)	Equivalent square spacing(m)	Initial spacing (stems ha^{-1})
Buffer	12.35	/	/
1	14.20	1.98	2551
2	16.31	2.28	1924
3	18.75	2.26	1457
4	21.54	3.00	1111
5	24.75	3.46	835
6	28.44	3.97	635
7	32.68	4.56	481
8	37.56	5.24	364
9	43.16	6.03	275
10	49.59	6.92	209
Buffer	56.99	/	/

The trees had not received thinning at any stage prior to examination. Due to natural mortality, windthrow or malformation, 385 of the original 450 trees were suitable for examination. A total of 182 trees had a complete set of neighbours. The 65 trees assessed for BIX and internode length were selected from this population.

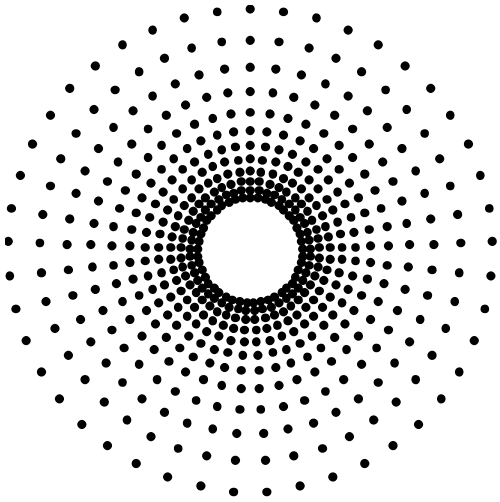

Figure 3.1. Plan of the Nelder spacing design experiment. Trees are planted at each spot.

Measurements

Measurements of diameter at breast height, tree height and crown height were made for the 385 trees. Diameter was measured using a tree diameter tape, whilst tree height and crown height were measured using a vertex height instrument. Crown height was interpreted as the first live whorl. Branch diameter and internode length was measured on 65 trees which had been felled. The 65 trees selected represented a combination of the five breed/cutting treatments and seven of the initial stand spacings. The largest branch in each quadrant at every whorl in the second log (6.0 - 12.0 m) was measured using callipers two centimetres from the trunk so that node swelling was minimised as a factor. Quadrant 1 always faced true north. Internode lengths for each log (6.0 - 12.0 m) were obtained from internodes that were completely within the log length mentioned above by measuring the vertical distance from the top of one whorl to the base of the whorl above. Values of internode length were averaged to determine the mean internode length for each tree.

Data Analysis

All analyses were undertaken using SAS (SAS Institute, 2000). Mean values of the block level data were used for all analyses unless otherwise indicated. An analysis of variance examined the main and interactive effects of spacing and breed on diameter, height, slenderness and distance to canopy. The mean was determined for all variables to assess what impact spacing and breed had on the variables and a Student-Neuman-Keuls (SNK) test was used to determine if the means were significantly different.

By taking into account repeated measures within trees a linear mixed model (proc MIXED) was used to assess the effect of height to the base of the internode on internode length. As internode length was not found to vary with height, subsequent analyses were undertaken at the block level using average internode length.

The effects of spacing and breed on BIX were initially assessed using analysis of variance. The continuous variables tree diameter and mean internode length were then included in the model to see if these terms could account for variation in BIX attributable to spacing and breed.

Plots of residuals were examined for bias. Residual values were plotted against predicted values and independent variables.

RESULTS

Initial stand spacing had a highly significant ($P<0.0001$) influence on tree diameter at breast height, with diameter increasing over two-fold from 17.7 to 36.6 cm as stand spacing declined (Table 3.2). Tree height was not significantly affected by stocking ranging from 16.6 m at 209 stems ha^{-1} to 18.4 m at 481 stems ha^{-1}. Crown height was also found to be very significantly influenced by spacing ($P<0.0001$), and exhibited a curvilinear relationship, which flattened off at higher stockings (Figure 3.2). Another stem characteristic found to be significantly influenced by spacing was stem slenderness ($P<0.0001$), with slenderness exhibiting a uniform increase with increasing stocking.

Table 3.2. Mean diameter, height, crown height and slenderness by initial stand spacing.

Initial spacing (stems ha^{-1})	Mean diameter (cm)	Mean height (m)	Crown height (m)	Slend-erness (m/cm)
209	36.6	16.6	1.8	0.46
275	34.7	17.5	2.7	0.51
364	35.0	17.7	3.4	0.51
481	31.8	18.4	5.4	0.59
635	28.6	18.0	6.9	0.64
835	24.9	17.7	7.8	0.74
1111	24.0	17.8	8.8	0.77
1457	21.9	17.6	9.3	0.84
1924	18.9	16.8	9.4	0.95
2551	17.7	17.3	10.2	1.03

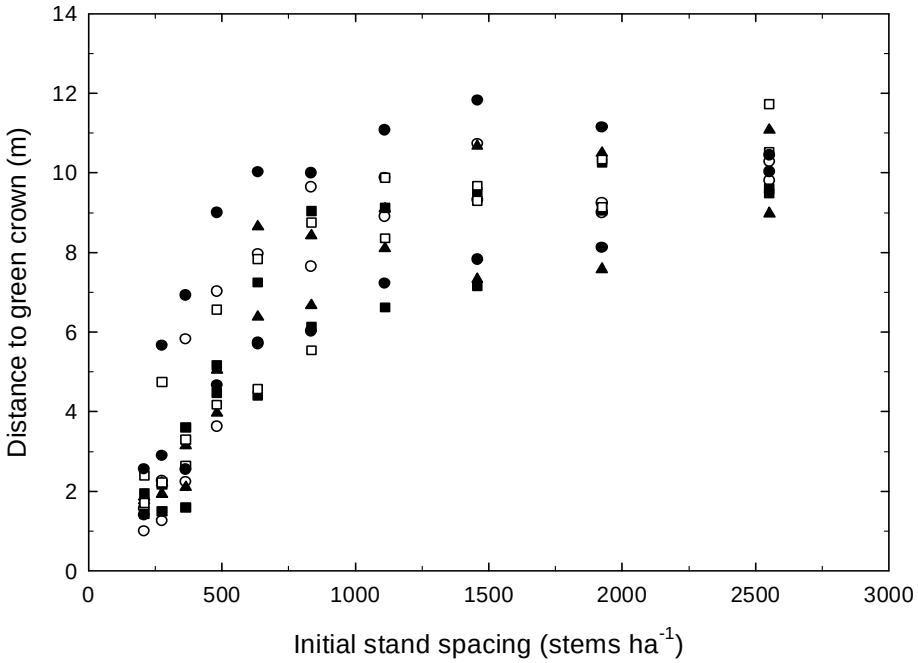

Figure 3.2. Relationship between initial stand spacing and distance to green crown for each breed/cutting treatment; three-year-old cuttings (black circle), one-year-old cuttings (white circle), 850 breed (black square), 870 breed (white square) and 268 breed (black triangle).

The influence of breed/cutting treatment on diameter was marginally significant (P=0.0418), with the 850 series displaying the largest mean diameter (29.4 cm), whilst the 870 series and the three-year-old cuttings exhibited the lowest mean diameter (26.3 cm) (Table 3.3). Tree height was not significantly by breed, although the 850 series demonstrated a noticeably greater mean height than the remaining treatments. The effect of breed on crown height was not significant. Stem slenderness

was marginally (P=0.0211) influenced by breed. The three-year-old cuttings were slightly more slender than other breed/cutting treatments.

Table 3.3. Mean diameter, height, crown height and slenderness by breed/cutting treatment.

Breed/ cutting treatment	Mean diameter (cm)	Mean height (m)	Crown height (m)	Slend-erness (m/cm)
1-year-old	27.2	17.6	6.6	0.70
3-year-old	26.3	17.5	7.3	0.75
268	27.8	17.4	6.3	0.68
850	29.4	18.2	6.0	0.68
870	26.3	17.1	6.7	0.71

Interactions between spacing and breed/cutting treatments were not statistically significant for diameter, height, slenderness and crown height.

Internode length was significantly influenced by breed (P<0.05) but not stocking or the interaction of the two. The 870 breed with a mean length of 61 cm across all stand spacings was significantly different from the four remaining breed/cutting treatments, which had mean lengths between 37 and 47 cm. The height to the base of the internode was found to have no influence on internode length. Internode length was not significantly correlated with diameter.

Initial stand spacing significantly influenced BIX (P<0.0001), with values for BIX ranging from 35 mm at 364 stems ha^{-1} to 13 mm at 2551 stems ha^{-1}. Neither breed or the interaction of breed and initial stand spacing had a significantly influence on raw BIX means.

Tree diameter exhibited a strong (r^2=0.80) significant (P<0.0001) positive relationship with BIX (Figure 3.3). Inclusion of stem diameter in the model accounted for the stocking effect on BIX; the latter effect was found to be insignificant when added to the model with stem diameter.

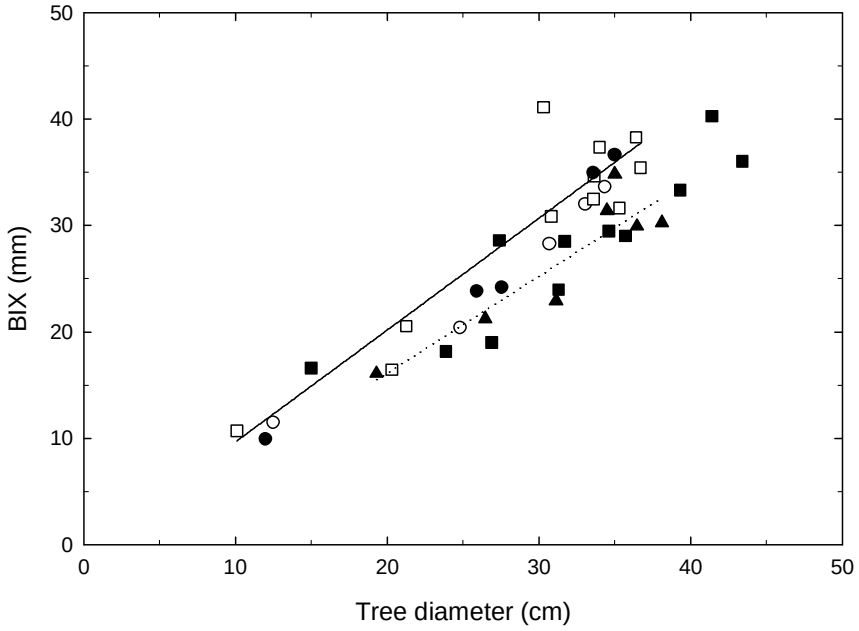

Figure 3.3. Relationship between BIX and tree diameter for the five breed/cutting treatments; three-year-old cuttings (black circle), one-year-old cuttings (white circle), 850 breed (black square), 870 breed (white square) and 268 breed (black triangle). Linear lines have been drawn through those breeds with the highest and lowest BIX for a given diameter; the 870 breed (solid line) and the 268 breed (dotted line), respectively.

Examination of the regression of BIX against stem diameter showed that for a given diameter, BIX differed considerably between breeds (Figure 3.3). Analysis of covariance indicated that breed significantly influenced the intercept between BIX and diameter ($P<0.01$), but not the slope ($P>0.05$). After adjustment was made for diameter, BIX exhibited a 5.5 mm range between breeds, with the 870 series and 268 series, representing the breeds with the highest and lowest BIX for a given tree diameter, respectively.

After correction had been made for tree diameter, a plot of residual BIX against mean internode length revealed a positive relationship (Figure 3.4). Mean internode length was significant ($P<0.0001$) when included in the model with stem diameter (also $P<0.0001$) and improved the coefficient of determination of this model from 0.80 to 0.90. Inclusion of mean internode length in the model accounted for the breed effect on BIX; the latter effect was found to be insignificant when added to the model with stem diameter and mean internode length.

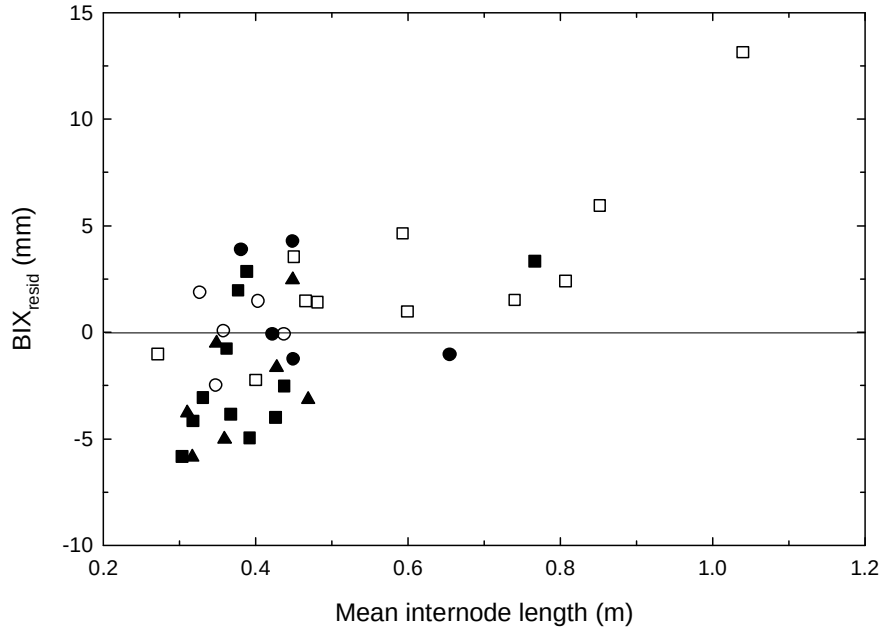

Figure 3.4. Relationship between residual BIX and mean internode length for the five breed/cutting treatments; three-year-old cuttings (black circle), one-year-old cuttings (white circle), 850 breed (black square), 870 breed (white square) and 268 breed (black triangle).

DISCUSSION

The results obtained provide considerable insight into how spacing regulates stem geometry. As stem geometry (diameter, height, stem slenderness, branch index) is an important concern for forest managers, demonstration of the effect of a wide range of operationally used spacings on these important external tree characteristics is useful. Spacing had a significant impact on diameter, crown height, stem slenderness and BIX, whilst breed marginally affected diameter and stem slenderness but significantly affected internode length.

Competition through stand spacing acts to reduce the growth rates of all individuals by the same proportion. This results in plants at high stockings showing less unequal size distribution than plants at lower stockings. This generalised statement applies to trees within this trial. Greatest variations in dimension occurred for diameter, slenderness and branch size at higher stockings, whilst tree height and crown height showed minor variation at high stockings.

Both Jayawickrama *et al.* (1997b) and Carson and Inglis (1988) stated that the 870 breed tended to grow more slowly than GF trees. This was consistent with the study reported here. Both GF breeds (850 and 268 series) demonstrated greater diameter and height growth than the 870 series. The 850 and 268 series had a mean diameter that was 3.1 cm and 1.5 cm larger respectively than the 870 breed, whilst the 850 and 268 series displayed a mean height that was 1.1 m and 0.3 m taller respectively. The differences in diameter were not statistically different, however, the 850 series was statistically different from the 870 series for mean height. The use of cuttings within this trial showed that the cuttings were neither superior nor inferior to the seedlings for any of the measured properties.

Diameter, as one would expect, was considerably affected by initial stand spacing. There was an almost uniform decrease in diameter with increasing stocking that resulted in over a two-fold increase in diameter. This relationship between stocking and diameter has been known for considerable time but it is still routinely confirmed, more recently from the Tikitere Agroforestry Trial (Knowles *et al.*, unpubl), and from work by Holley and Stiff (2003) and Land *et al.* (2003) using loblolly pine (*Pinus taeda*).

No relationship was found between tree height and initial stand spacing. Variation in mean height varied little between the ten stockings (16.6 - 18.4 m) within this trial. This result corroborates previous observations (Siemon *et al.*, 1976; Hocker, 1979; Cremer *et al.*, 1982; Lanner, 1985). However, it contradicts Sjolte-Jorgensen (1967), Mason (1992), Maclaren *et al.* (1995) and Carson *et al.* (1999), who all noted that mean height increased with increasing stocking in their observations of trials.

Crown height showed a substantial change of nine metres between the low and high stand spacings, with significant differences existing between spacings for crown height up to 1111 stems ha^{-1}, after which changes in crown height were less pronounced. A roughly uniform increase of one metre was found between spacings for the first seven rings of the Nelder plot representing 209 to 1111 stems ha^{-1}. Beekhuis (1965) noted that both Brown (1962) and Whiteside (1962) had observed an approximate one metre increase in crown height for every 0.3 m increase in spacing,

which was similar to results observed here. There was no evident relationship between tree height and crown height, which was to be expected as crown height is a response variable to spacing and tree height was shown to have no correlation with stand spacing.

Slenderness was also significantly influenced by spacing. It is well established that in general, in trees of the same age, slenderness decreases with increasing diameter (Sjolte-Jorgensen, 1967; Wang and Ko, 1998; Zhang *et al.*, 2002). In this trial, more than a two-fold increase in slenderness occurred between the lowest and highest stand stockings.

The significant influence of initial stand spacing on branch index for the second log in this trial corroborates findings by Tombleson *et al.* (1991) and Ballard and Long (1988). Findings demonstrate that variation in BIX between stockings was attributable to differences in diameter. This is consistent with previous studies which show that diameter accounts for variation in spacing induced differences in BIX (Smith, 1986; Knowles and Kimberley, unpubl; Woollons *et al.*, 2002). For a given diameter the greatest difference in BIX between breeds was between the 268 and 870 series. The BIX for the 870 breed was found to be on average 5.5 mm larger than the 268 breed after adjusting for stem diameter. This is supported by Carson and Inglis (1988), Jayawickrama *et al.* (1997b) and Watt *et al.* (2000) who have all found that for a given tree diameter the 870 breed tended to have larger diameter branches than GF trees. Carson and Inglis (1988) state that selection for long internodes increased average internode length but also tended to increase average branch size, which can be supported from observations made in this trial.

Mean internode length accounted for the within and between breed effect on BIX. This is consistent with research by Watt *et al.* (2000), and extends these findings to a greater range of stockings and breeds. Analyses done at the tree level (data not shown) indicate that the relationship between mean internode length and BIX was strongest for the 268, 870 and 850 series. For these breeds our results suggest that inclusion of internode length in models of branch diameter may provide a useful means of quantifying within and between breed variation in BIX.

The effect of spacing on internode length agrees with findings by Siemon *et al.* (1976) and Tombleson *et al.* (1991) who observed no obvious trend. Compared to many other conifers, a distinctive feature of *Pinus radiata* is the relatively long internodes which separate the whorls of branches (Lavery, 1986), that are under strong genetic control once the juvenile state of the tree is passed (Lavery, 1986; Grace and Carson, 1993). The effect of breed on internode length was well demonstrated within this trial and compared favourable with results from Carson and Inglis (1988), who noted that the 870 breed had significantly longer mean internode lengths than the 850 breeding series.

Carson and Inglis (1988) noted that the 268 series was extremely multimodal, but this observation was not consistent with results reported here. The 850 and 268 series had an essentially identical number of whorls per tree throughout the trial, whilst as expected, the 870 breed had considerably fewer whorls. Correlations in this study suggest that internode length of *Pinus radiata* may be relatively independent of tree size, which is in agreement with Woollons *et al.* (2002). In attempting to model internode length, Woollons *et al.* (2002) noted that 'it is evident internode length can be regarded as a random phenomenon'. Results from this study and previously from Carson and Inglis (1988) confirm that there is a large potential for exploiting genetic variation in internode length to dramatically increase the yields of clearwood, without unduly compromising growth rate. There are obvious advantages in growing clearwood in long pieces, namely, reducing the costs of re-cutting and increasing the versatility of the product for meeting a range of end uses.

CONCLUSIONS

- No statistically significant interactions between spacing and breed were found for any of the variables examined.

- Diameter, crown height and slenderness were all significantly influenced by initial stand spacing. Stem diameter decreased from 36.6 cm to 17.7 cm as stand stocking increased from 209 stems ha^{-1} to 2551 stems ha^{-1}. Mean crown height increased from 1.8 m to 10.2 m with increasing stand

stocking, whilst stem slenderness increased from 0.46 to 1.03 m cm^{-1} with increasing stand stocking.

- The 850 breeding series had a longer canopy than any of the other breed/cutting treatments, and also had the largest mean diameter, although the effect on diameter was only just statistically significant.

- BIX was positively correlated with tree diameter. After adjustment was made for tree diameter, BIX was positively correlated with internode length, and the two variables together explained 90% of variation in BIX.

- The 870 breed had significantly longer internode lengths than the other breed/cutting treatments demonstrating its defining physical characteristic. The 870 breed had a mean internode length of 61 cm, whilst the remaining four breed/cutting treatments had mean internode lengths which ranged from 37 cm to 47 cm.

Chapter 4

Modelling the influence of initial stand spacing and breed on outerwood modulus of elasticity of 17-year-old *Pinus radiata*

INTRODUCTION

An important element of wood quality is "stiffness", which is also known as modulus of elasticity (MOE). The usefulness of structural timber is strongly related to MOE (Kumar, 2004). The longitudinal modulus of elasticity is the most commonly measured property to define elastic behaviour of wood and measures the resistance of wood to deformation under an applied load. MOE is often considered more important than strength (modulus of rupture) for predicting wood quality of *Pinus radiata* because boards rarely break in normal use; much more frequently a load results in excessive deflection (Walford, 1985).

Low stiffness of *Pinus radiata* limits utilisation options, and is more prevalent when the species is grown on the short rotations that are favoured by fertile sites and silvicultural regimes that are designed for rapid attainment of piece-size specifications (Burdon *et al.*, 2001). Consequently, two important decisions affecting stiffness made during establishment of a forest plantation are the selection of appropriate genetic material and initial stand spacing. Research has revealed that both of these factors have a significant influence on MOE (Wang and Ko, 1998; Zhang *et al.*, 2002; Lasserre *et al.*, 2005),

Initial spacing can have a major influence on stem characteristics and intrinsic wood properties, and thus the quality of the products yielded from the plantation. The effect of spacing on MOE has received limited attention, although examples of such work is scattered in the literature (Wang and Ko, 1998; Zhang *et al.*, 2002; Lasserre *et al.*, 2004). Stand dynamics, coupled with tree morphology and anatomy is markedly affected by initial stand spacing, however, the consequent effect of initial spacing on stiffness is not well understood. Past research for numerous species has found that

MOE scales positively with stand stocking. This is the case for Japanese cedar (*Cryptomeria japonica*) (Wang and Ko, 1998), black spruce (*Picea mariana*) (Zhang *et al.*, 2002) and 11-year-old *Pinus radiata* (Lasserre *et al.*, 2004).

Stand spacing may affect MOE through numerous mechanisms. The identification of possible mechanisms is on-going as is determining to what degree these possible mechanisms influence MOE. Windflow is believed to affect MOE as it is an important component of a tree's physical environment that is influenced by stand spacing. Closer spacings lower stem deflection through reducing wind speed within the canopy and by dampening stem oscillations as the canopies of neighbouring trees buffer each other (Cremer *et al.*, 1982). Pruyn *et al.* (2000) found that increased stem movement induced by wind, reduced MOE in *Populus trichocarpa*, whilst Telewski and Jaffe (1986) have stated there is a clear tendency for a decrease in MOE of the stem in response to wind. Stand spacing also strongly influences radial growth rate which in turn is thought to influence MOE by altering microfibril angle through the proportion of earlywood within a tree, as well as having a direct effect on microfibril angle within earlywood. Green canopy and the role that auxins, a major plant growth regulator, play in earlywood/latewood formation, as well as tracheid elongation in conjunction with gibberellin is another possible mechanism influencing MOE formation (Larsen, 1962; Mason, 2006). Recent research (Watt *et al.*, 2006b) also suggests that taper or stem slenderness may regulate MOE. The Euler buckling formula suggests that in a competitive situation increases in stem slenderness require that trees increase MOE in order to reduce the risk of critical failure of the stem. When light demanding species such as *Pinus radiata* are grown with high levels of competition, rapid height growth is important to ensure they are not overtopped by neighbours. Under high levels of stand stocking trees become etiolated as priority is given to height growth at the expense of diameter increment, thus a tree will undergo elastic buckling unless MOE increases (Watt *et al.*, 2006a). It is hypothesised that trees are able to sense and respond to higher compressive stress as a result of greater height growth and thus produce new wood with higher MOE, possibly by manipulating the angle of cellulose microfibrils in the secondary cell wall (Watt *et al.*, 2006b).

Genetics also strongly influence MOE, which has seen the current attention of tree breeders more focused on stiffness and stability, which are now accepted as top priorities for solid wood breeding (Jayawickrama *et al.*, 1997a; Sorensson *et al.*, 1997). Preliminary studies on a small number of samples by Matheson *et al.* (1997) and Shelbourne (1997) have found high heritabilities for MOE in *Pinus radiata*. Individual-tree heritability estimates for MOE of 0.53 by Kumar *et al.* (2002), compared favourably to those reported by Matheson *et al.* (1997), however, these values are almost double that reported by Kumar (2004) who sampled a greater number of specimens. Variation in MOE in clonal material is wide, and studies have shown that *Pinus radiata* corewood values for MOE at age 10 may range 4.3 GPa or 198% between different clones (Sorensson *et al.*, 2002). Given this high heritability, and the wide variation observed across clonal material, breeding and clonal selection has the potential to markedly enhance MOE.

Forest growers are interested in how stand stocking and genetics interactively influence MOE. Lasserre *et al.* (2005) observed that while genotype and spacing both significantly influenced MOE, these factors did not significantly interact, indicating that genotype and stand stocking had an additive effect on MOE. Previous studies examining such interactions are limited as spacing studies tend to exclude genetic populations as a factor, whilst genetic trials use limited spacings to allow for greater and more accurate assessment of the genetic material (Carson *et al.*, 1999). This study utilises the unique design of a Nelder spacing trial (Nelder, 1962) which allows for interactions between plant spacing and genetic populations to be examined more fully. The wide range of genetic material and stand spacings used in the trial reported here provided an opportunity for a much greater analysis of these two variables and their relative influence on MOE of *Pinus radiata*, than had been previously carried out.

Path analysis can be used to partition the influences that stem dimensions have on stiffness if a suitable causal model can be developed. This was carried out to determine to what degree did stem dimensions influence stiffness of the trees examined. A hypothesised model of MOE outlining linkages between MOE, stem slenderness, diameter, height, and distance to the green crown is outlined in Figure 4.1. Within this model predictive variables may influence MOE directly (solid line), indirectly, whereby their effect is mediated through another variable (dotted line), or

both directly and indirectly. As stem slenderness, diameter and distance to the green crown are known to influence MOE, direct pathways have been drawn from these variables to MOE. Direct pathways have been drawn from diameter and height to stem slenderness. The direct pathway drawn from diameter to green crown height, assumes diameter acts as a surrogate for stand density, which has a well documented effect on green crown height (Beekhuis, 1965). Given that tree height also affects green crown height (Beekhuis, 1965) a direct pathway has been added between these variables.

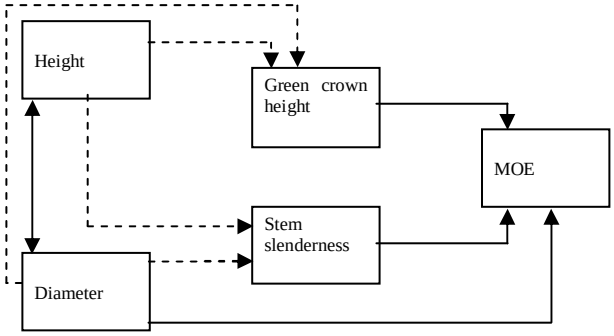

Figure 4.1. Proposed causal pathways linking tree dimensions and modulus of elasticity. Solid lines represent direct pathways of influence, while dashed lines represent indirect pathways of influence on modulus of elasticity. The double headed arrow between height and diameter indicates a covariance.

The objectives of this study were to (i) determine the main and interactive effects of initial stand spacing and breed on outerwood stiffness and (ii) partition the direct and indirect effects of diameter, stem slenderness, tree height and distance to the green crown on outerwood stiffness.

MATERIALS AND METHODS

Location

Measurements were taken from 17-year-old *Pinus radiata* trees that had been grown in an Nelder experiment (Nelder, 1962) located at Burnham, approximately 18 km south-west of Christchurch (latitude 43°36.5'S, longitude 172°17.75'E, altitude 70 m a.s.l.). The trial was situated on Lismore stony silt loam soil (N.Z.S.B., 1968) and experienced a mean annual precipitation of 650 mm, in which seasonal water deficits do occur during January to March, when evapotranspiration exceeds rainfall (G. Furniss, pers. comm.).

Experimental Plot

The experiment comprised five breed/cutting treatments, including seedlings from the 850, 870, and 268 breeding series and cuttings taken from one-year-old and three-year-old parents. Both the one and three-year-old cuttings were from the 268 series. The Nelder contained 45 spokes separated by 8 degree intervals in 10 circular rings (Figure 4.2) with high initial stocking rates present at the centre of the Nelder to low initial stocking rates present on the outer ring of the Nelder (Table 4.1). Each breed/cutting treatment occupied nine of the spokes split in a group of five spokes on one side of the plot and a group of four spokes on the other side of the plot.

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Buffer	56.99	/	/

The trees had not received thinning at any stage prior to examination. Due to natural mortality, windthrow or malformation, 385 trees were suitable for examination.

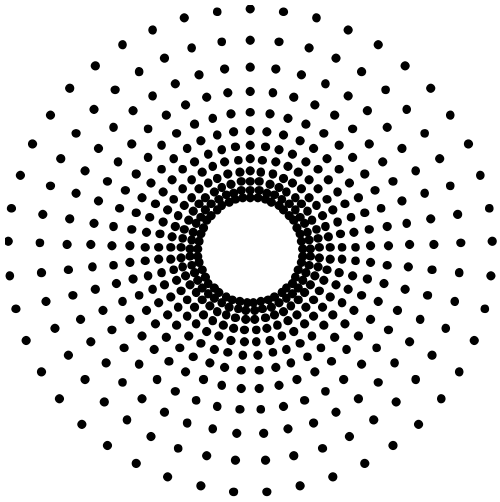

Figure 4.2. Plan of the Nelder spacing design experiment. Trees are planted at each spot.

Three of the most widely planted series within New Zealand are the 268, 850 and 870 breeding series. As these genotypes were developed between twenty to forty years ago they now constitute a large proportion of mature *Pinus radiata* within New Zealand. The 268 and 850 series were predominantly selected for good stem form, multinodal branch habit and fast diameter growth, and are from the same breed. Physiologically aged cuttings were developed within the 268 series to provide greater stability at time of planting and in the early years of growth as they have thicker stems and thicker, more stable roots. The 850 breeding series had a growth and form (GF) rating of 14, whilst the seedlings, one-year-old cuttings and three-year-old cuttings from the 268 breeding series had GF ratings of 22, 19 and 17, respectively. The GF rating reflects a seedlots relative genetic worth for growth and stem form, with growth given twice as much weight as stem form (Carson, 1996). A relatively unimproved seedlot will have a low GF rating. These GF breeds were devised to be good for structural timber and, when pruned, knot-free timber. However, their selection resulted in the reduction of the average internode length below that of unimproved plantations, thus the development of a special purpose “long internode” breed, the 870 breed (Jayawickrama *et al.*, 1997b). This breed is designed for longer internodes in an

effort to obtain long clear sections from unpruned trees. None of these breeds were bred with improved stiffness properties in mind.

Measurements

Measurements of diameter at breast height, tree height and crown height were taken immediately prior to measurements of modulus of elasticity (MOE). Green dynamic modulus of elasticity (GPa) was determined for 385 sample trees between 0.5 and 2.0 metres up the stem using the time of flight technique.

MOE can be measured in standing trees using non-destructive acoustic techniques. Transit time or stress wave velocity was determined on all standing trees by time of flight using the portable instrument TREETAP (Version 4), a non-destructive acoustic tool developed at the University of Canterbury, New Zealand (Figure 4.3).

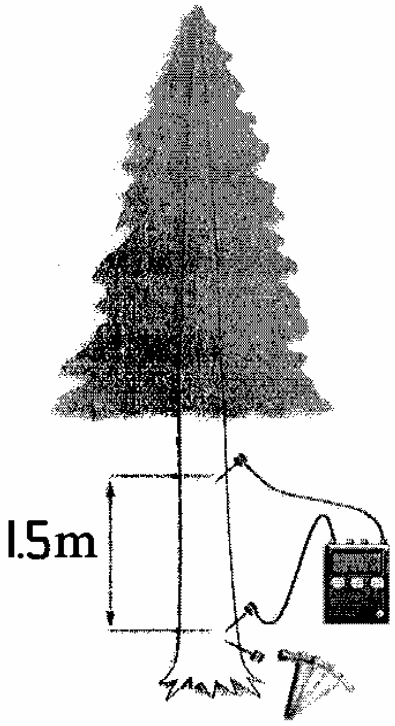

Figure 4.3. A schematic outline of the measurements undertaken on standing trees using time of flight instrument, TREETAP.

The use of non-destructive techniques to assess the properties of wood provides obvious benefits. A variety of acoustic tools are available to assess the properties of

wood including MOE, but only time of flight tools provide a way of assessing the properties of standing trees (Ross, 1999). Time of flight tools use in-situ stress wave measurements to provide stress wave information that can be used to assess the mechanical properties of wood in standing trees. The method can only estimate MOE within the few outermost growth rings (Andrews, 2000), however, useful relationships between stress wave velocity measurements and properties of trees, logs and lumber have been observed (Huang, 2000; Wang *et al.*, 2000a). Studies have found a strong relationship between standing tree MOE obtained by time of flight measurements and MOE measured in small clear wood specimens (Ross, 1999; Yamamoto, 2000). Lindstrom *et al.* (2002) found a strong correlation existed between time of flight generated MOE and MOE from traditional static bending (r^2=0.96).

Transit time was measured on both the windward and leeward sides of the standing tree without removing the bark. Two probes connected to the TREETAP were inserted in the butt log of the tree at a distance of 1.5 m from each other. A third probe was inserted lower in the stem at approximately 0.15 m from the lower probe. This third probe was tapped and the velocity of sound was measured between the other two probes. TREETAP detects the acoustic wave as it passes the first stop transducer and starts a timer which records the time it takes for the wave to reach the second stop transducer placed a known distance from the first. The time delay and the distance between the two sensors allow the stress wave velocity to be calculated. The velocity measurement was repeated eight times for each side of the tree (i.e. 16 measurements per tree) as this improves the consistency of the stress wave velocity through the outerwood and thus the estimate of dynamic outerwood MOE for each tree.

The following equation was applied to estimate MOE:

$$MOE = \rho V^2$$

where ρ is green density (kg m^{-3}) and V is stress wave velocity (m s^{-1}). Stress wave velocity was determined from sample length (l) and transit time (t) as; $V = l\, t^{-1}$.

Green density was calculated from a sample of 38 discs taken at 1.4 metres above ground level from selected trees representing a combination of breeds and initial stand spacings. At time of felling 30 mm discs were taken for the 38 trees. Green density was determined as green weight/green volume, using the immersion technique. From analyses of these measurements, green density was found to vary with neither breed nor stocking and mean density was 935 kg m^{-3} (± 8.2 kg m^{-3}).

Data Analysis

All analyses were undertaken at the plot level using SAS (SAS Institute, 2000). Values of MOE were averaged across both sides of the tree, before plot means were determined. An initial analysis of variance was conducted to examine the main and interactive effects of stand spacing and breed on stem dimensions and MOE. Multiple range testing was undertaken using the Student-Neuman-Keuls (SNK) test.

Univariate relationships between MOE and the continuous variables diameter, tree height, distance to canopy and stem slenderness were examined using appropriate functional forms, both between and within breeds to determine which variables were significantly related to MOE. Analysis of covariance was used to determine how well each variable accounted for the effects of stand spacing and breed on MOE.

To control for the effects of common cause, path analysis was used as an extension to regression analysis, using the CALIS procedure (SAS Institute, 2000). Path analysis is a multivariate statistical technique which bridges the gap between empirical observation and theoretical research. This technique requires development of a preconceived causal model in which directional flow and the inter-relationships among independent (exogenous) and dependent (endogenous) variables are specified, as outlined in Figure 4.1. A more complete description of path analysis is given in Wright (1921, 1934), Li (1975) and Rao and Morton (1980).

Path analysis was used to determine the significance of pathways in Figure 4.1. Non-significant pathways, denoted by *t*-values of less than 1.96 were removed from the model. After all non-significant pathways were removed model statistics were examined. For the overall model values of the chi-square ratio greater than 0.05

indicate an acceptable fit between model and data. However as the chi-square statistic has some limitations as an inferential test (see Kaplan 1990, for review), the goodness of fit index, normed fit index and comparative fit index (CFI) were also used to determine the adequacy of the model fit to the data. All of these indices range from 0 to 1, with values over 0.9 indicating an acceptable fit between model and data. A model exhibiting acceptable fit between the model and the data also has normalised residuals which are less than 2.

RESULTS

MOE was found to be significantly influenced by both spacing (P<0.0001) and breed (P<0.0001). Examination of the partitioned sums of squares revealed that spacing had the greater influence on MOE. Values of MOE scaled positively with stand stocking by 39% across the range in stand stocking. There was a rapid linear increase in MOE from 5.4 GPa at 209 stems ha^{-1} to 7.2 GPa at 835 stems ha^{-1}, after which the rate of increase in MOE with further increases in stand stocking declined, reaching 7.5 GPa at 2551 stems ha^{-1} (Table 4.2).

Table 4.2. Influence of initial stand spacing on MOE. Each value shown is the mean ± standard error. Means followed by the same letter are not significantly different at P<0.05.

Initial spacing (stems ha^{-1})	Mean MOE (GPa)	SNK grouping
209	5.4 (0.24)	A
275	5.7 (0.25)	AB
364	5.9 (0.18)	AB
481	6.6 (0.22)	BC
635	6.7 (0.30)	BC
835	7.2 (0.41)	C
1111	7.1 (0.27)	C
1457	7.1 (0.30)	C
1924	7.6 (0.21)	C
2551	7.5 (0.26)	C

The significant influence of breed/cuttings was mainly attributable to the high values of MOE recorded for the cuttings (Figure 4.4). Modulus of elasticity was lowest for the 850 and 268 series, with values averaging 6.1 and 6.3 GPa, respectively. The average respective MOE values for the 870 breed and one-year-old cuttings of 6.6 and

6.7 GPa, substantially exceeded that of the 850 and 268 series. The three-year-old cuttings had an average MOE of 7.7 GPa, which significantly exceeded the one-year-old cuttings and seedlings from the 870, 268 and 850 series by 15, 17, 22 and 27%, respectively. No significant interaction (P>0.05) was found between breeding series and stand spacing (Figure 4.4).

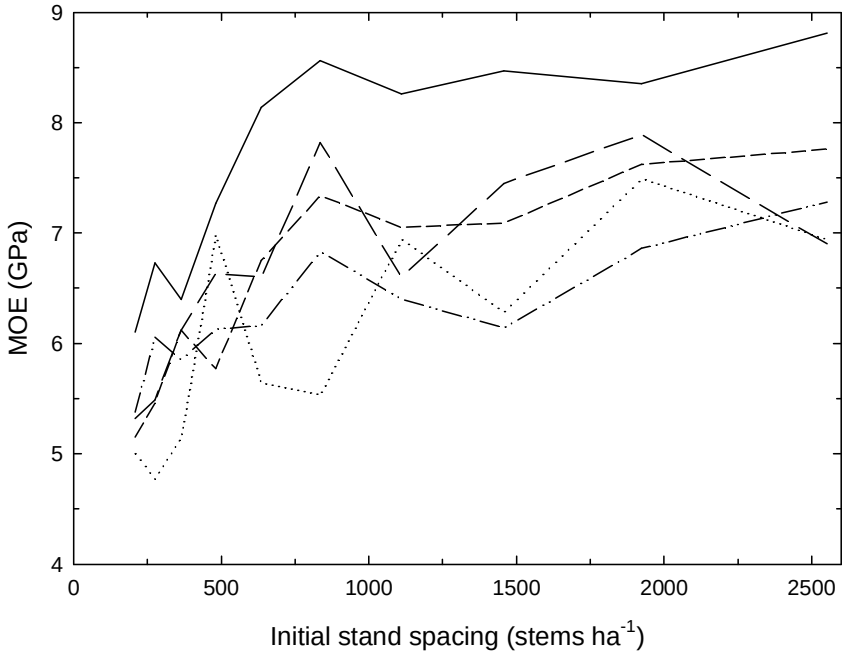

Figure 4.4. Relationship between mean MOE and initial stand spacing for the five breed/cutting treatments; three-year-old cuttings (solid line), one-year-old cuttings (long dash), 870 breed (short dash), 268 breed (dot) and 850 breed (dash-dot-dot-dash).

No significant interaction (P>0.05) was found between breed and stand stocking. The propagation influence on MOE between the three-year-old cuttings and the breed exhibiting the lowest MOE values, the 850 series, ranged from 1.87 GPa at 2551 stems ha^{-1} to 1.1 GPa at 209 stems ha^{-1}. The maximum difference between the three-year-old cuttings and the 850 series was 3.03 GPa at 835 stems ha^{-1}.

The MOE variation between the windward (6.56 GPa) side of all trees was significantly different (P=0.0015) from the leeward (6.9 GPa) side of all trees. Of the tree dimensions examined, stem slenderness exhibited the strongest significant (P<0.0001) relationship with MOE. Stem slenderness exhibited a positive relationship with MOE (Figure 4.5), which accounted for 49% of the variance in the data.

Distance to the green crown was significantly and positively related to MOE (Figure 4.6), accounting for 46% in the data. When distance to the green crown was expressed as a percentage of tree height the coefficient of determination increased marginally to 0.48. Diameter exhibited a significant (P<0.0001) negative linear relationship with MOE (Figure 4.7), accounting for 44% of the variance in MOE. Height was not significantly related to MOE. Within breeds, stem slenderness was more closely related to MOE than diameter or distance to the green crown for all five breed/cutting treatments, with coefficients of determination ranging from 0.4 for the 268 series to 0.87 for the 870 breed.

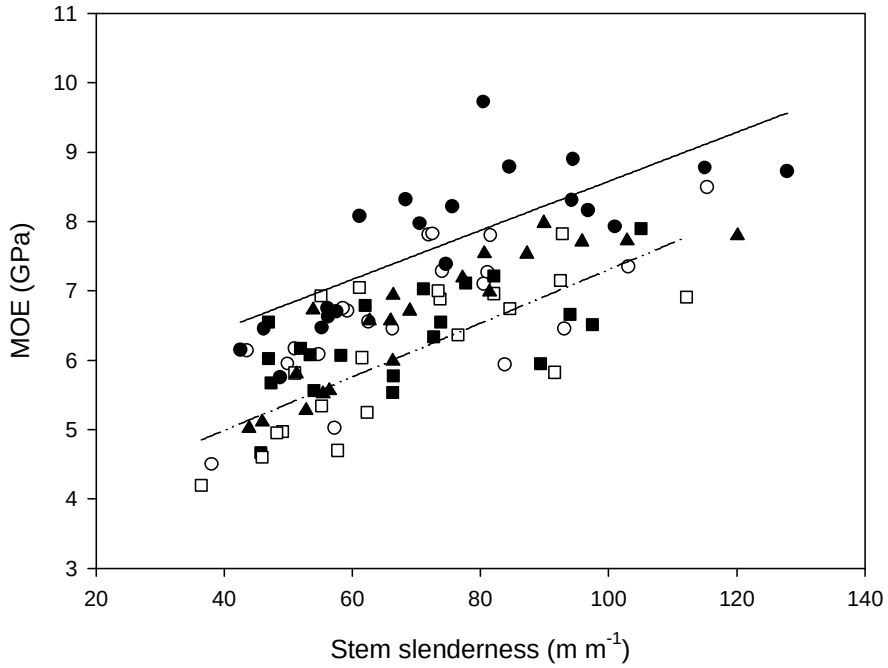

Figure 4.5. Relationship between modulus of elasticity and stem slenderness for three-year-old cuttings (black circles), one-year-old cuttings (white circles), seedlings from the 268 (black squares), 850 (white squares) and 870 (black triangles) breeding series. Linear lines have been drawn through data for the three-year-old cuttings (solid line) and 850 breed (dash-dot-dot-dash) as after correction has been made for stem slenderness, these represent the breeds with the highest and lowest MOE, respectively.

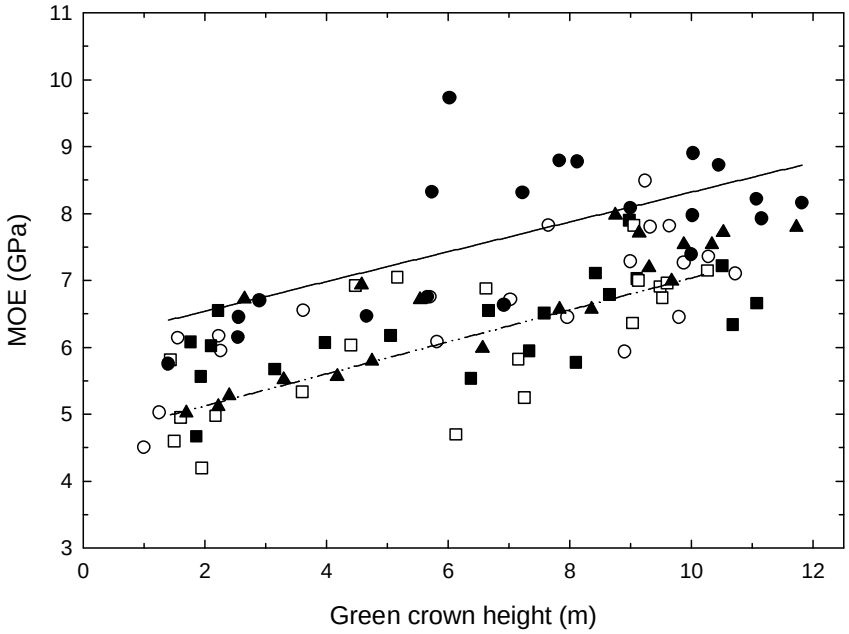

Figure 4.6. Relationship between modulus of elasticity and green crown height for three-year-old cuttings (black circles), one-year-old cuttings (white circles), seedlings from the 268 (black squares), 850 (white squares) and 870 (black triangles) breeding series. Linear lines have been drawn through data for the three-year-old cuttings (solid line) and 850 breed (dash-dot-dot-dash) as after correction has been made for green crown height, these represent the breeds with the highest and lowest MOE, respectively.

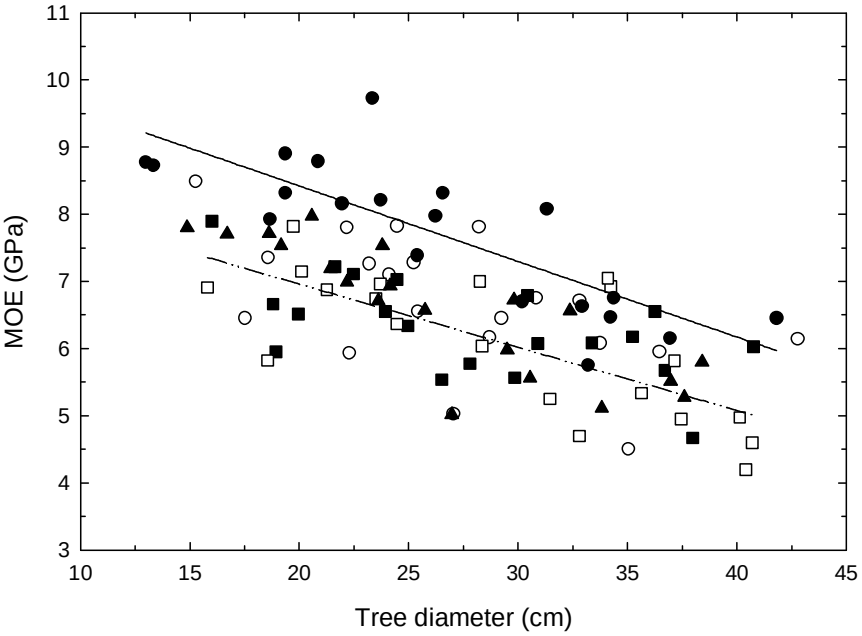

Figure 4.7. Relationship between modulus of elasticity and diameter for three-year-old cuttings (black circles), one-year-old cuttings (white circles), seedlings from the 268 (black

squares), 850 (white squares) and 870 (black triangles) breeding series. Linear lines have been drawn through data for the three-year-old cuttings (solid line) and 850 breed (dash-dot-dot-dash) as after correction has been made for diameter, these represent the breeds with the highest and lowest MOE, respectively.

Analysis of covariance showed that when included singly in the model, diameter and green crown height accounted for the effect of stand spacing on MOE. Although stand spacing was still marginally significant ($P<0.05$) in the predictive model of MOE with stem slenderness, stand spacing added very little explanatory power (partial $r^2=0.02$). In contrast, addition of breed was highly significant ($P<0.001$) for univariate relationships between MOE and stem slenderness, diameter and distance to the green crown (expressed as a proportion of tree height), with breed accounting for an additional 15, 20, and 18% of the variance in MOE respectively.

Path analysis was used to test the significance of the relationships outlined in the initial model, described in Figure 4.1. As the pathway between MOE and diameter was insignificant ($P>0.05$; t value = 0.11) this pathway was dropped from the initial model.

For the modified model outlined in Figure 4.8, an acceptable level of model fit to the data was demonstrated by all goodness of fit indices (all >0.98) and the chi-square ratio ($P=0.44$). None of the normalised residuals exceeded 1.l in magnitude. In addition all remaining pathways in the model were significant (t values >1.96).

Path coefficients within the modified model (Figure 4.8) indicated that tree slenderness had a slightly higher direct influence on MOE than distance to the green crown (path coefficients of 0.40 vs. 0.35). Relationships of both these variables to MOE were positive. Although diameter and height did not directly influence MOE, they did have significant indirect effects on MOE via stem slenderness and green crown height. The final model explained 53% of the variance in MOE, 91% of the variance in stem slenderness and 82% of the variance in green crown height (Figure 4.8).

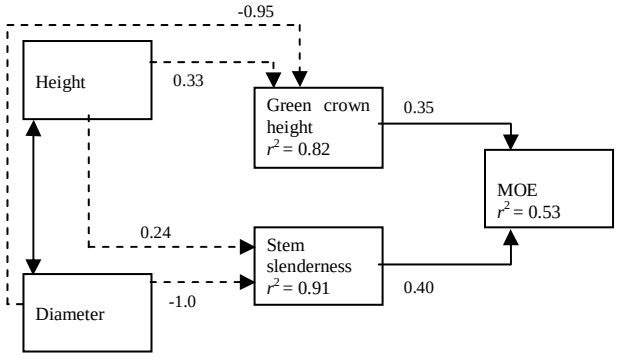

Figure 4.8. Final path analysis model, with significant (P<0.05) pathways shown. Solid lines represent direct pathways of influence while dashed lines represent indirect pathways of influence. Values next to each line give the path coefficient for that pathway. The amount of variance (r^2) explained for each endogenous variable is shown.

DISCUSSION

This study shows considerable variation in *Pinus radiata* MOE between spacings. The substantial improvement in MOE with increasing stocking is consistent with findings in other coniferous species over comparable spacing levels (Wang and Ko, 1998; Chuang and Wang, 2001; Zhang *et al.*, 2002). For *Pinus radiata*, previous research (Lasserre *et al.*, 2004) has found that stand stocking scales positively with MOE in the outermost rings of 11-year-old trees, between stand spacings of 835 and 2500 stems ha^{-1}. Data used in this study from 17-year-old trees indicates a less pronounced gain across this stand stocking range (6% vs. 42%) which suggests that outerwood MOE between these stand stockings will converge with age, possibly as competition in the lower stand stockings increases. Our research extends these previous findings by Lasserre *et al.*, (2004) to the commonly used operational stand spacings of between 209 and 835 stems ha^{-1} over which MOE increased by 33%. This result indicates that managers have considerable control over outerwood MOE in mature wood on dryland sites through selection of appropriate stockings.

The considerable gain in MOE for the three-year-old cuttings and the moderate gain in MOE for the one-year-old cuttings over seedlings suggest that a possible source of MOE improvement may be through propagation technique and physiological age.

Although physiological age is the main difference between the cuttings, they originated from different seedlots and have different GF ratings, thus possibly impacting on the relative difference in MOE obtained from these two treatments. Menzies *et al.* (2004) observed that acoustic velocity at breast height (as an indicator of stiffness) increased significantly and consistently with increasing physiological age. Given that cuttings from more mature trees show more adult-like morphological characteristics, such as declining microfibril angle up the stem, than seedlings, one would expect wood in cuttings, for given ring numbers from the pith, to match that of wood of a point higher up in seedlings. On that basis, one would expect the butt logs of cuttings with maturation to have lower microfibril angle and greater MOE (Burdon *et al.*, 2004).

There was no significant interaction between stand spacing and breed, which indicates that silviculture and breeding can be used as complementary approaches to improve MOE. The lack of an interaction concurs with Lasserre *et al*. (2004) who found that no significant interaction between stand stocking and clonal genotype existed in 11-year-old *Pinus radiata*. Further research should investigate whether the lack of interaction between breed and stand stocking is maintained along the length of the stem.

MOE is believed to be influenced by numerous mechanisms that interact. The identification of these mechanisms is the topic of on-going research, however, evidence to date suggests that a number of these possible mechanisms may contribute to MOE formation. Whilst these mechanisms were not specifically examined in this research, the strong influence that was found between stem slenderness and green crown height on MOE further strengthens the developing belief by many that these factors directly influence MOE formation, whilst casting doubt on the importance of diameter as a direct influence on MOE.

A significant negative relationship was found between rate of growth and MOE in this study. This observation has also been noted in other studies for Douglas fir (*Pseudotsuga menziesii*) (Walford, 1985) and 11-year-old *Pinus radiata* (Lasserre *et al.*, 2004). Low initial stocking, which increases radial tree growth, has been postulated to result in an increase in the relative proportion of the stem occupied by

the juvenile corewood which exhibits poor MOE values (Shelbourne, 1997). It is has been proposed that radial growth affects the proportion of anticlinal versus periclinal cell divisions and may therefore affect microfibril angle (J. Walker, pers. comm.). However, exactly how the cell divisions impact on microfibril angle is unknown. Lindstrom *et al.* (1998) found that the normal trend of pith to bark decrease in microfibril angle can be interrupted by a surge in growth rate such as may occur following thinning or removal of competing trees. This has led to the suggestion that suppression of juvenile growth could contribute to a reduction of the amount of wood with high microfibril angle in a tree at harvest. This relationship may also be explained by the variation in latewood percentage between trees of high and low diameter. Previous research has shown that trees with a high diameter have a lower percentage of latewood and lower density than trees with a low diameter (Chuang and Wang, 2001). As latewood fibres display a higher MOE than those of earlywood, the lower incidence of latewood in larger trees could account for the observed low MOE within these larger diameter trees.

Whilst all this evidence supports radial growth rate as a possible mechanism for MOE, Lasserre (2005) observed that when comparing *Pinus radiata* at two sites with almost perfectly equivalent yields but separated by two years of age, radial growth apparently did not affect MOE. Although there was an age difference, diameter at both sites was indistinguishable, as was MOE, suggesting that increased radial growth rate at the younger site, did not have an impact on MOE. Further research that would contradict radial growth as a mechanism for MOE development comes from Watt *et al.* (2006a, 2006b) who observed that stem diameter was positively correlated with MOE. Furthermore, results from this study suggest that variation in MOE across stand stocking gradients may be the direct result of spacing induced changes on stem slenderness and green crown height, and that diameter only indirectly affects MOE through these variables.

The significant positive influence of distance to the green canopy on MOE found in this study is consistent with previous research. In a study which included a range of pruned heights Mason (2006) found that distance to the green crown exhibited a significant positive relationship with MOE. Distance to the green canopy within this Nelder experiment was found to be significantly and positively correlated with MOE,

however, distance to canopy as an impacting factor on MOE could not be accurately assessed in this experiment, as it was a response variable as a result of competition induced through spacing.

The mechanism by which green crown height influences MOE has been outlined by Larson (1962) and Brown (1971) who hypothesised that auxins produced by both the green foliage and developing buds strongly influence corewood formation. The production of large diameter earlywood cells is dependent upon relatively high auxin concentrations, where the current season's growth and the internodes immediately beneath it form juvenile wood (Zobel and van Buijtenen, 1989). With increasing distance down the stem, cell size gradually decreases, and at lower internodes, true latewood is produced as the auxin stimulus originating from the terminal meristems becomes more limiting. This however, is not the only factor impacting on latewood formation. As the growth period advances, auxin synthesis continues to decline and latewood cells can be found at higher and higher internodes in the tree. Proceeding down the tree, auxin synthesis not only decreases but the branch distance over which the stimulus must be translocated to the main stem increases so that the lower branches contribute less and less auxin to the supply of the main trunk (Larson, 1962). These lower auxin concentrations result in thicker cell walls, longer fibre length and decreased fibril angle; properties which all contribute to increased MOE (Herman, 2005). Therefore, trees with high crowns such as those in highly stocked stands may produce lower proportions of earlywood in the bole and greater proportionate quantities of higher density latewood (Larson, 1962) with improved wood properties. This hypothesis has been further strengthened by observations from Megraw (1985), who observed that as the vigorous crown moved upwards, faster earlywood to latewood transition occurred, resulting in greater wood density in areas below the crown.

Auxins also play a role in tracheid elongation. Kalev and Aloni (1998) observed that gibberellin, a growth hormone, in the presence of auxin promoted tracheid elongation in leaves and the stem (Herman, 2005) by stimulating growth of both the upper and lower ends of the tracheid. Tracheid length is known to be inversely related with microfibril angle, a known major influencing factor on MOE, with very strong correlations having been observed (r^2>0.9) between tree species (Echols, 1955;

Erickson and Arima, 1974; Donaldson, 1992). Furthermore, in addition to tracheid length affecting microfibril angle, it is also seen to influence density, another known major factor impacting on MOE, as some studies have proposed that greater wood density could be partly explained by longer and thicker tracheids (Dutilleul *et al.*, 1998).

Green canopy may affect MOE not only through auxin gradients, but also though its impact on stem slenderness, which has been recognized as a mechanical explanation of stiffness development (Watt *et al.*, 2006a). Numerous studies of stem form have shown that trees with long, vigorous crowns produce strongly tapering stems with a rather high proportion of earlywood to latewood. As the crown recedes, owing either to advancing age, stand closure, or artificial pruning, the stem becomes more cylindrical and the proportion of earlywood to latewood decreases. If the hypothesis is accepted that auxin gradients regulate the size of the wood elements within an annual ring, then it is logical to extend this hypothesis to include an auxin regulating influence over increment distribution as well (Larson, 1962). Radial expansion of xylem and phloem elements has been observed below an application point of auxin (Sundberg *et al.*, 2000) which explains why the maximum radial growth occurs in the general vicinity of the live crown base, which results in small crowned trees being more cylindrical as opposed to the strongly tapered stems of trees with long, vigorous crowns (Larson, 1962).

Of the tree dimensions examined slenderness was found to be most strongly related to MOE. Theory suggests that the positive relationship observed between MOE and stem slenderness occurs as trees growing in very dense stands with high slenderness require high MOE to mitigate the possibility of stem buckling through self weight. Although no buckling was observed within the Nelder trial, the possibility of buckling was quite real for trees planted at the highest stand stockings as individual tree stem slenderness reached values of up to 175 m m^{-1}, which exceed all previously reported values within the literature (Holbrook and Putz, 1989; Niklas, 1994a). In an adjacent 17-year-old stand of trees planted at 10 000 stems ha^{-1}, 13% of the trees exhibited buckling (M. Watt, pers. comm.). Stem slenderness for twenty of these buckled trees (determined as Ht/DBH), exhibited a range from 122 to 178 m m^{-1} (M. Watt, pers. comm.), which is

comparable to tree slenderness values at the upper end of the range found in our study (range of 28 to 175 m m^{-1}).

Although diameter has often been used to predict MOE within sites for trees growing under competition, there is considerable evidence to suggest that the effects of diameter and height on MOE are mediated through slenderness. The relationship between stem slenderness and diameter depends on the circumstances in which trees are grown. Considerable research has investigated how stand spacing variation in spacing trials within a single site influences MOE at a given age. As with this research, these studies typically conclude that increasing stand stocking has little effect on height growth, but does reduce diameter growth markedly, which results in increases in slenderness (Zhang *et al.*, 2002; Lasserre, 2005). This research shows these increases in slenderness across stand stocking gradients to be positively related to MOE. As has been previously found, the correlation of MOE with diameter is negative (Chuang and Wang, 2001: Zhang *et al.*, 2002; Lasserre *et al.*, 2005), and MOE exhibits little correlation with height (Zhang *et al.*, 2002; Lasserre, 2005).

Relationships between MOE and diameter and height have been found to be quite different across site gradients. The recent study by Watt *et al.* (2006a) into variation in *Pinus radiata* MOE of trees grown across a nationwide environmental gradient at the same high stand stocking found height, diameter and slenderness to be positively correlated to MOE, with slenderness exhibiting the strongest correlation with MOE (r^2=0.61). Most of the variation in slenderness was attributable to between-site variation in height as height growth was far more responsive to improving site conditions than diameter growth. Taken together these results demonstrate the disparity in relationships between diameter and MOE and height and MOE. These results also suggest that both the effects of site conditions and within-site competition levels on MOE are at least partially mediated through changes in slenderness, when trees are grown at high stockings. In the study reported here and that by Watt *et al.* (2006a), slenderness was found to exhibit a positive correlation with MOE. It is quite likely in both cases that increases in slenderness induced increases in MOE to reduce the risk of stem buckling.

The relationship between the possible mechanisms discussed above and their influence on MOE will undoubtedly be complex. Thus, it will be difficult to determine what mechanisms contribute what proportion, if any, to development of MOE gradients within trees. However, the now recognised importance of stiffness as a wood quality variable will ensure the continued work of examining the mechanical and management influences on MOE.

Results from this trial, in addition to those from Lasserre *et al.* (2004), unquestionably show that greater MOE can be achieved from higher stockings. Gains in MOE were also achieved through the use of physiologically aged cuttings. The process of growing plantation products is driven by economics, therefore, to use stockings comparable with those used at the high stand stockings used in this trial, financial penalties would be incurred compared to use of low stockings. However, the possibility of implementing regimes using higher stocked stands needs to be further investigated. Similarly, the use of physiologically aged cuttings over standard seedling material would incur greater cost at time of establishment. Stiffness is a fundamentally important wood property which affects customer perceptions of value in both structural and appearance products, and thus improvement and greater controllability of stiffness may justify these greater growing costs in some circumstances. By developing management regimes in which genetic breeds with higher stiffness wood are used along with stand spacings that achieve a compromise between sufficient final stem size and higher stockings, then the industry can look to increase profitability through better utilisation of products.

CONCLUSIONS

- Distinguishable increases in MOE (39%) were achieved with increased stand stocking. The majority of this gain (33%) occurred between 209 and 835 stems ha^{-1}.

- Gains in MOE were also exhibited through the use of different propagation techniques; namely the use of cuttings over seedlings, with cuttings of greater physiological age displaying greater MOE.

- Differences in MOE between seedlings and cuttings of greater physiological age were greater at higher stand stockings.

- No significant interaction was found to exist between initial stand spacing and breed. Any interaction between spacing and breed that existed was greatest at the highest stand stocking where differences in MOE between breed were most evident.

- Stem slenderness (r^2=0.49) explained the greatest amount of variation in MOE, followed by distance to the green crown (r^2=0.46) and diameter (r^2=0.44).

Chapter 5

Influence of initial stand spacing and breed on vertical distribution of wood stiffness in 17-year-old *Pinus radiata*

INTRODUCTION

Wood stiffness or longitudinal modulus of elasticity (MOE) is one of the most important wood properties for solid timber applications (Evans and Ilic, 2001). As a result, stiffness has been recognised as an important property of *Pinus radiata* timber that requires greater attention due to potential lost earnings by the industry arising from poor performing, low stiffness timber.

Radial changes in stiffness throughout a stem in *Pinus radiata* have been well documented (Tsehaye, 1995; Xu and Walker, 2000), with MOE in *Pinus radiata* increasing radially from the pith to the cambium, with the greatest rate of change occurring near the pith. However, vertical changes in stiffness are less conspicuous. Vertical changes in MOE show no obvious difference along the vertical direction of the stem as noted by Tsehaye (1995) and Tsehaye *et al.* (2000), whilst Xu and Walker (2000) observed no real apparent change after approximately three metres up the stem. The butt log, up to approximately three metres up the stem, has been identified as a zone of low stiffness. However, as stiffness varies radially, one would expect variation up a tree because the radius of a stem diminishes with height. The observed lack of change in stiffness vertically up the stem as observed by Tsehaye (1995), Tsehaye *et al.* (2000) and Xu and Walker (2000) might be a surprise in view of the increasing preponderance of corewood up the stem and the decline in the values of most physical characteristics. This could be attributed to averaging within the stem section. The corewood at the base of the stem is significantly less stiff than elsewhere in the tree, but the butt log has also both more and stiffer outerwood to compensate; whereas at the top of the stem the corewood is somewhat stiffer, but there is only little outerwood of moderate stiffness (Buchanan *et al.*, 1999).

The localised reduction in MOE at the base of the tree up to approximately three metres up the stem as reported by Hirakawa and Fujisawa (1996), Perstorper (1996) and Xu and Walker (2000) has been suggested to serve a functional purpose (K. Niklas, pers. comm.). It has been suggested that the base of tree acts as a "hinge" to allow trees the ability to sway when external forces are applied. Niklas speculated that the localised reduction in MOE was adaptive in terms of wind-induced bending moments which allow the trunk to bend in the wind.

Although stiffness gradients in *Pinus radiata* have received increased attention in the recent past, there has been no reported previous research investigating the impact of different initial stand spacings, breeding series, propagation techniques and physiological age of cuttings on the vertical distribution of stiffness in *Pinus radiata*. This is supported by Jayawickrama (2001) who states that few studies have examined variation in MOE up the stem of *Pinus radiata* trees.

Wood properties have become a major thrust in New Zealand's *Pinus radiata* breeding programmes due to a realisation that there will be significant benefits in having improved wood properties in future forests (Sorensson *et al.*, 1997). Selections of seedlots in recent times have focused on wood quality issues as demonstrated by the development of a 'high density breed' and a 'structural timber breed'. Preliminary studies on small numbers of entries by Matheson *et al.* (1997) and Shelbourne (1997) found high heritabilities for MOE for *Pinus radiata*. Individual-tree heritability estimates for MOE of 0.53 by Kumar *et al.* (2002), compared favourably to those reported by Matheson *et al.* (1997), however, these values are almost double that reported by Kumar (2004) who sampled a greater number of specimens. Given this heritability for MOE, genetics has the potential to markedly enhance MOE. Whilst examining the outerwood of *Pinus radiata* (Chapter 4), it was observed that cuttings were stiffer than seedlings, with cuttings of greater maturation, having higher MOE than younger cuttings. Whether this influence will eventuate when examining vertical variation in MOE is unknown as no previous findings examining this connection have been found in the literature.

Initial stand spacing has been found to influence MOE (Wang and Ko, 1998; Zhang *et al.*, 2002; Lasserre *et al.*, 2004). Research has found that MOE increases with stocking for Japanese cedar (*Cryptomeria japonica*) (Wang and Ko, 1998), black spruce (*Picea mariana*) (Zhang *et al.*, 2002), juvenile *Pinus radiata* (Lasserre *et al.*, 2004) and mature *Pinus radiata* (Chapter 4). MOE up the stem has been examined in Norway spruce (Bruchert *et al*., 2000) and was found to decrease up the stem, especially above 50% of stem height. No apparent research has examined the impact that stand spacing has on the vertical distribution of MOE up the stem in *Pinus radiata*.

The objective of this study was to examine the main and interactive effects of initial stand spacing and breed on vertical variation in MOE of *Pinus radiata*.

METHODS AND MATERIALS

Location

Measurements were taken from 17-year-old *Pinus radiata* trees that had been grown in a Nelder experiment (Nelder, 1962) located at Burnham, approximately 18 km south-west of Christchurch (latitude 43°36.5'S, longitude 172°17.75'E, altitude 70 m a.s.l.). They were situated on Lismore stony silt loam soil (N.Z.S.B., 1968) and experienced a mean annual precipitation of 650 mm, in which seasonal water deficits do occur during January to March, when evapotranspiration exceeds rainfall (G. Furniss, pers. comm.).

Experimental Plot

The experiment comprised five breed/cutting treatments, including seedlings from the 850, 870, and 268 breeding series and cuttings taken from one-year-old and three-year-old parents. Both the one and three-year-old cuttings were from the 268 series. The Nelder contained 45 spokes separated by 8 degree intervals in 10 circular rings (Figure 5.1) with high initial stocking rates present at the centre of the Nelder to low initial stocking rates present on the outer ring of the Nelder (Table 5.1). Each breed/cutting treatment occupied nine of the spokes split in a group of five spokes on one side of the plot and a group of four spokes on the other side of the plot.

Table 5.1. Nelder design.

Circle number	Radii of planting circles(m)	Equivalent square spacing(m)	Initial spacing (stems ha^{-1})
Buffer	12.35	/	/
1	14.20	1.98	2551
2	16.31	2.28	1924
3	18.75	2.26	1457
4	21.54	3.00	1111
5	24.75	3.46	835
6	28.44	3.97	635
7	32.68	4.56	481
8	37.56	5.24	364
9	43.16	6.03	275
10	49.59	6.92	209
Buffer	56.99	/	/

The trees had not received thinning at any stage prior to examination. Due to natural mortality, windthrow or malformation, 385 trees were suitable for examination.

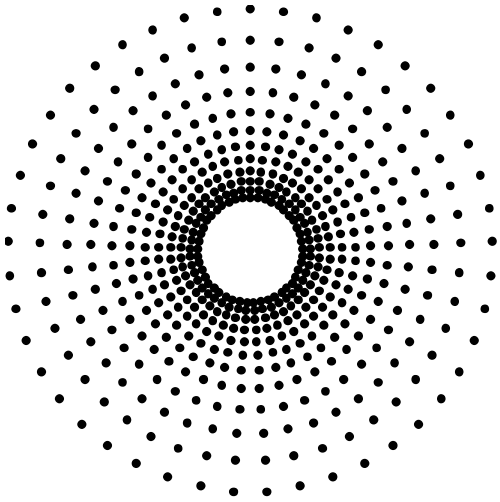

Figure 5.1. Plan of the Nelder spacing design experiment. Trees are planted at each spot.

Three of the most widely planted series within New Zealand are the 268, 850 and 870 breeding series. As these genotypes were developed between twenty to forty years ago they now constitute a large proportion of mature *Pinus radiata* within New Zealand. The 268 and 850 series were predominantly selected for good stem form, multinodal branch habit and fast diameter growth, and are from the same breed. Physiologically aged cuttings were developed within the 268 series to provide greater stability at time of planting and in the early years of growth as they have thicker stems and thicker, more stable roots. The 850 breeding series had a growth and form (GF) rating of 14, whilst the seedlings, one-year-old cuttings and three-year-old cuttings from the 268 breeding series had a GF rating of 22, 19 and 17, respectively. The GF rating reflects a seedlots relative genetic worth for growth and stem form, with growth given twice as much weight as stem form (Carson, 1996). A relatively unimproved seedlot will have a low GF rating. These GF breeds were devised to be good for structural timber and, when pruned, knot-free timber. However, their selection resulted in the reduction of the average internode length below that of unimproved plantations, thus the development of a special purpose “long internode” breed, the 870 breed (Jayawickrama *et al.*, 1997b). This breed is designed for longer internodes in an

effort to obtain long clear sections from unpruned trees. None of these breeds were bred with improved stiffness properties in mind.

Measurements

Measurements of diameter at breast height, tree height and crown height were taken immediately prior to measurements of modulus of elasticity (MOE). Seventy-two trees representing the five different breed/cutting treatments and six of the initial stand spacings were selected. Three repetitions of each of the breed by spacing interactions were sought. The felled trees were completely surrounded by neighbouring trees. All felled stems were de-limbed and cut into two metre long bolts up the entire length of the stem (Table 5.2). Small end diameter and large end diameter was measured using callipers for all bolts. Assessment of wood velocity for all two metre bolts (n=543) from the seventy-two felled trees was carried out using HITMAN, which provided a volume weighted average of velocity (Harris and Andrews, 1999).

Table 5.2. Bolt number and corresponding height (m) up the stem.

Bolt 1	Bolt 2	Bolt 3	Bolt 4	Bolt 5	Bolt 6	Bolt 7	Bolt 8
0-2	2-4	4-6	6-8	8-10	10-12	12-14	14-16

Velocity was assessed with the use of a resonance tool (HITMAN, Carter Holt Harvey Forests Limited, New Zealand). HITMAN (now called Director HM200) allows the operator to obtain measurements by holding the sensor against the end of a stem and hitting the same end with a hammer to induce a sound wave that travels down the length of the log and reverberates off the other end (Figure 5.2).

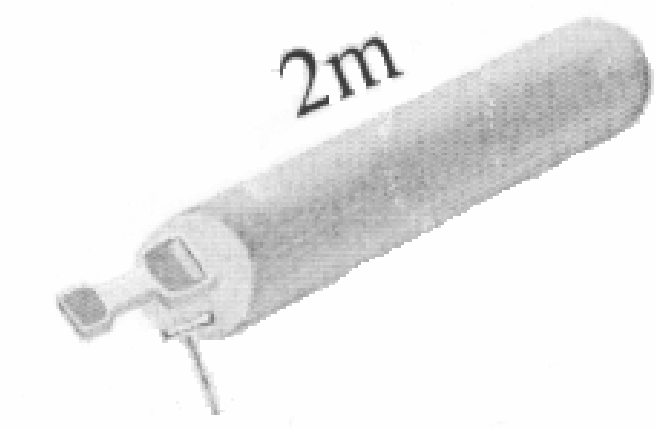

Figure 5.2. A schematic outline of the resonance measurement device, HITMAN.

HITMAN measures the audible frequency of sound waves (Kumar, 2004). The reverberation time measurement is based on multiple acoustic passes, up to several hundred, instead of only a single acoustic pass. The reverberation time is measured by the sensor and provides a direct measure of the log's stiffness; the stiffer the log, the faster the wave and vice versa (Harris and Andrews, 1999).

Lindstrom *et al.* (2004) found that resonance generated MOE was in close agreement with static MOE (r^2=0.96), whilst earlier observations by Lindstrom *et al.* (2002) found a correspondence between resonance generated MOE and MOE from traditional static bending to be very strong (r^2=0.98) and relatively unbiased ($y = 1.04x$).

The resonance measurement of velocity is a near perfect spatial average of the log, both in log length and cross sectional area. The impact resonance method usually determines the frequency of the reverberation by Fourier analysis of the measurement period i.e., the outcome is an average of the entire measurement period including the time to achieve plane wave response (Harris *et al.*, 2002).

Green dynamic modulus of elasticity (GPa) was determined using the following equation:

$$MOE = V^2\rho / 1000$$

where V^2 is velocity (km s^{-1}) and ρ is green density (kg m^{-3}).

Green density was calculated from a sample of 38 discs taken at 1.4 metres above ground level from selected trees representing a combination of breeds and initial stand spacings. At time of felling 30mm discs were taken for the 38 trees. Green density was determined as green weight/green volume using the immersion technique. From analyses of these measurements, green density was found to vary with neither breed nor stocking and mean density was 935 kg m^{-3} (± 8.2 kg m^{-3}).

Data analysis

All analyses were undertaken using SAS (SAS Institute, 2000). Using a MIXED model with a cross-over design, an analysis of variance was used to examine the effects of independent variables including spacing, breed, diameter, and stem slenderness on mean bolt MOE. The interactive effects of spacing and breed on MOE were also assessed. The generalised model used was:

$$Y_{ijkl} = u + S_i + B_j + (SB_{ij}) + D_k + SS_l + e_{ijkl}$$

where Y_{ijkl} is the dependent variable MOE, u is the overall mean, S is spacing, B is breed (SB) is the interaction between spacing and breed, D is stem diameter, SS is stem slenderness and e is the model error.

Plots of residuals were inspected for bias. Residual values were plotted against predicted values and independent variables. SAS procedure CAPABILITY was used to test for normality of residual frequency distributions.

Multiple regression analysis (MIXED model with a cross-over design) was used to determine what impact continuous variables such as large end diameter, mean bolt diameter and bolt slenderness had on MOE, whilst simple regression was used to determine the significance and strength of diameter at breast height, large and small end diameter, mean bolt diameter plus bolt slenderness, and two forms of whole tree slenderness on MOE at different spacings and between breeds.

RESULTS

Mean tree MOE, taken as the average of all bolts within a tree, was significantly influenced by initial stand spacing (P<0.0001). Examination of the partitioned sums of squares revealed that spacing had considerably greater influence on mean tree MOE than breed did. MOE scaled positively with stand spacing with MOE increasing from 5.18 GPa at 275 stems ha^{-1} to 6.96 GPa at 2551 stems ha^{-1} (Figure 5.3) or a 34% increase.

Mean tree MOE was also significantly influenced by breed (P<0.0001). The 870 breed was approximately 8% and 16% stiffer than the 268 and 850 breeding series, respectively. Propagation technique did not appear to influence MOE, however, the maturation status of the cuttings did, as the three-year-old cuttings were 7% stiffer than the one-year-old cuttings. Multiple comparison tests showed that within spacings, MOE between the breeds displayed a moderately uniform pattern.

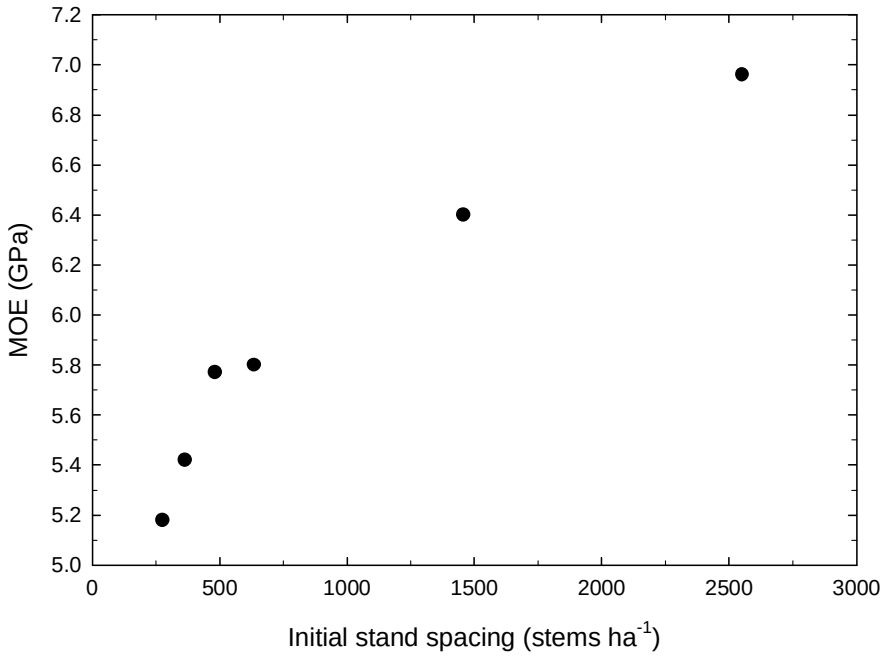

Figure 5.3. Relationship between mean tree MOE and initial stand spacing at the plot level.

A significant interaction (P<0.0001) between spacing and breed for MOE was present that could explain only a low proportion of the variation (r^2=0.32) in mean tree MOE. However, this interaction did not exist in any meaningful form. The breed treatments did not display uniform patterns of MOE within and between initial stand spacings.

The vertical distribution of MOE up the stem displayed a peaked pattern. Bolt 1 was found to be close to the weakest bolt (5.06 GPa) over the length of the stem, being only marginally stiffer than bolt 8 (5.02 GPa) at the top of the stem. Bolt 1 was 29% weaker than bolt 2 (6.54 GPa) and 31% weaker than bolt 3 (6.64 GPa), which was the stiffest bolt in the stem. After MOE had reached its maximum value at bolt 3, a gentle decline in bolt stiffness was observed to the top of the measured stem.

Spacing had a substantial impact on MOE up the stem. The MOE of the lowest bolt was greater with increased stocking, whilst all stockings had a similar MOE for the bolt at the top of the measured stem. It was at the top of the stem that the least amount of variation in MOE between the different stockings was present (Figure 5.4).

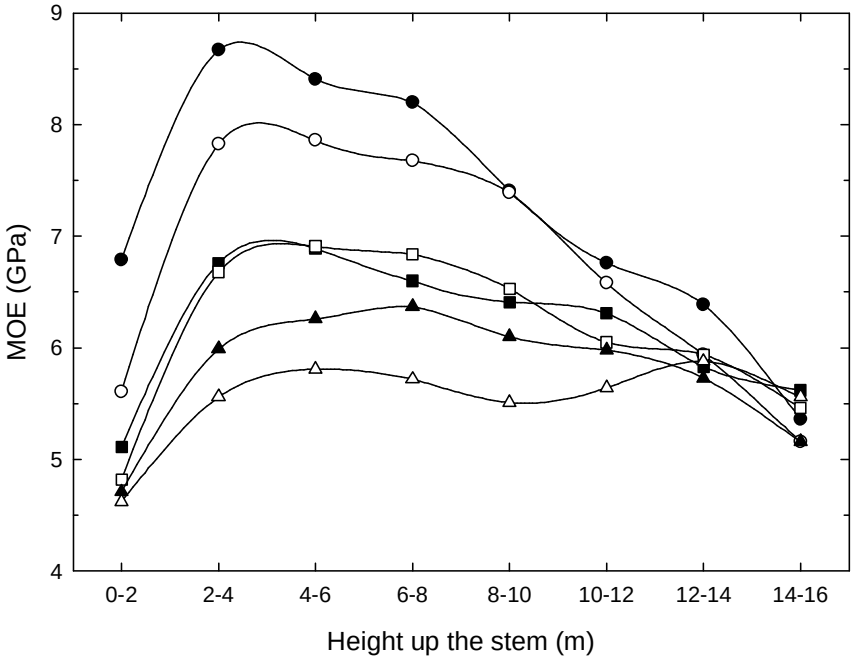

Figure 5.4. Plot of MOE up the stem at each initial stand spacing; 2551 stems ha^{-1} (black circles), 1457 stems ha^{-1} (white circles), 635 stems ha^{-1} (black squares), 481 stems ha^{-1} (white squares), 364 stems ha^{-1} (black triangles) and 275 stems ha^{-1} (white triangles).

The variation in MOE between stockings was greatest at bolt 2, where a 56% or a 3.11 GPa difference existed between 275 and 2551 stems ha^{-1}. The relative decrease in vertical MOE between the stiffest bolt in the tree and the weakest bolt in the tree was considerably larger at 2551 and 1457 stems ha^{-1} than for the remaining four stockings. The variation in MOE between the weakest and stiffest bolt within a tree was greatest at 2551 and 1457 stems ha^{-1}, where there was 58% difference in MOE, whilst at the remaining lower stockings, that difference was reduced to approximately 36% (Figure 5.4).

The interaction between breed and height up the stem on MOE was not significant (P=0.1381). All breed/cutting treatments displayed a substantially lower MOE in bolt

1 than in bolt 2. MOE remained relatively constant for all breed/cutting treatments between bolt 2 and bolt 4, before declining up the stem (Figure 5.5). The relative difference in MOE between the five breed/cutting treatments at all stand spacings remained largely constant.

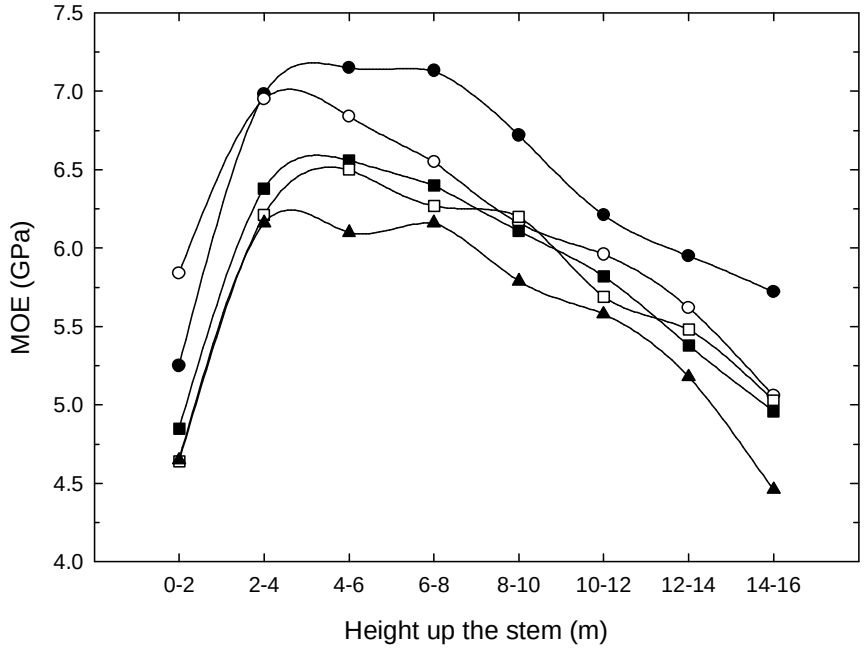

Figure 5.5. Plot of MOE up the stem for each breed/cutting treatment; 870 breed (black circles), three-year-old cuttings (white circles), 268 breed (black squares), one-year-old cuttings (white squares) and 850 breed (black triangles).

When tree height was normalised for all initial stand spacings, the portion of a tree that displayed the highest MOE increased vertically when stocking decreased. At stockings of 635 stems ha^{-1} or greater, the bottom 15% of the stem was of low MOE. The maximum MOE was obtained between 15% and 40% of stem height before declining to the top of the stem. At stockings of 481 stems ha^{-1} and less, the bottom 15% was again identified as being of low MOE. A transitional period towards the maximum MOE was present between 15% and 25% of stem height, whilst maximum MOE was obtained between 25% and approximately 50% of stem height before declining to the top of the stem.

Variations in the proportional height of MOE were also present for breed. All five breed/cutting treatments displayed low MOE up to 15% of stem height. Both the three-year-old and one-year-old cuttings exhibited maximum MOE between 15% and

30% of stem height before decreasing, whilst the 268, 850 and 870 breeding series obtained maximum MOE between 15% and 40% of tree height, before declining to the top of the stem.

Mean bolt MOE was significantly influenced (P<0.0001) by spacing for all bolts except those at the very top of the stem, whilst the effect of breed was only significant for bolt 1 and bolt 8 (P<0.05). Bolt slenderness expressed as bolt length/difference between large and small end diameter was found to have a significant (P<0.0001) correlation with bolt MOE, however, it only explained a low proportion (r^2=0.24) of the variation in MOE across all spacing treatments (Figure 5.6). Large and small end diameter plus mean bolt diameter (Figure 5.7) were all significant (P<0.0001), but only explained 7%, 3% and 5% of the variation in bolt MOE. Tree height was found to have no impact on bolt MOE, however, crown height did (P<0.0001) for all but the top two bolts (bolts 7 and 8).

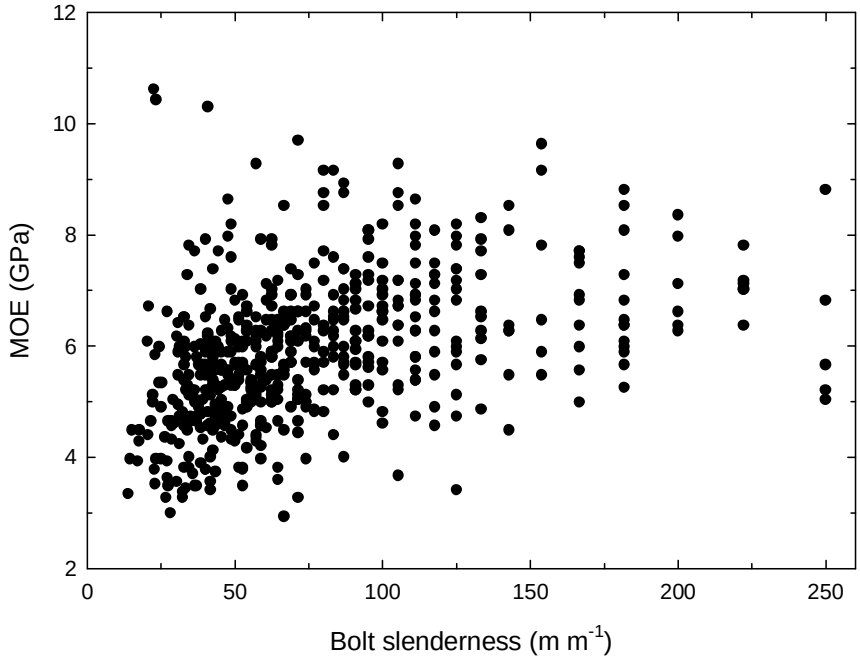

Figure 5.6. Relationship between MOE and bolt slenderness (bolt length/difference between large end diameter and small end diameter of bolt) for all bolts.

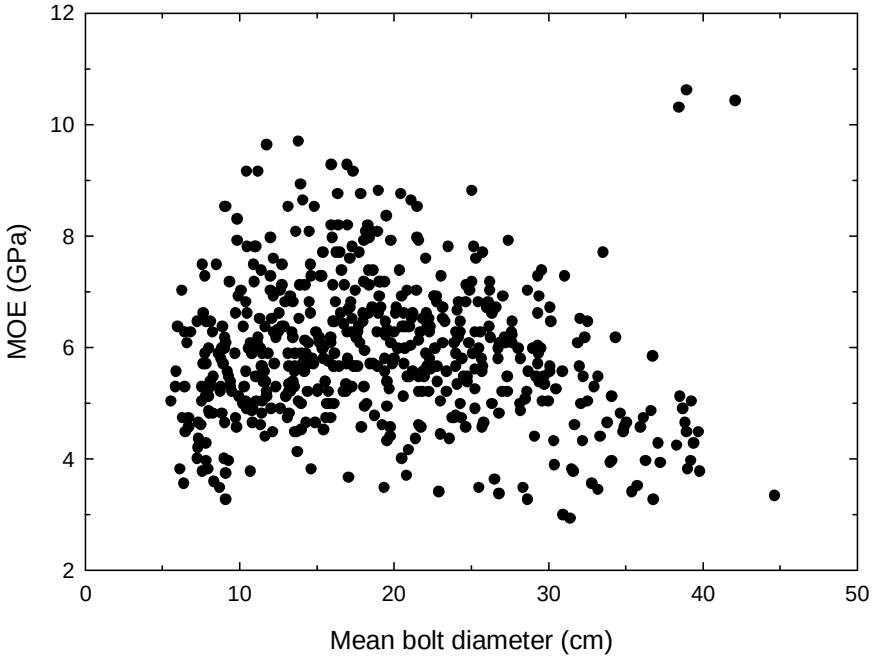

Figure 5.7. Relationship between MOE and mean bolt diameter for all bolts.

DISCUSSION

Previous work by Tsehaye (1995) and Xu (2000) examining vertical changes of whole stem MOE noted that no real apparent change up the stem was evident and that MOE values remained very consistent. This trial however, has found large variations in the vertical distribution of MOE. Tsehaye (1995) reported that there was no obvious difference in mean stiffness along the vertical direction of the stems, whilst Xu (2000) reported that in the vertical direction, stiffness rises from the ground line and reaches the mean stiffness of the stem at a height of approximately 2.7 metres. Thereafter, the variation of stiffness in the vertical direction was insignificant.

The lowest portion of the tree (bolt 1) was often found to exhibit the lowest MOE values of any part of the tree within this trial and had MOE values considerably lower (29%) than that of the second bolt. This pattern has also been noted by Xu (2000), who found that in the butt log, up to 2.4 - 2.7 metres, the average stiffness values were inferior to those found elsewhere in the stem. Furthermore, after MOE had reached its maximum value at bolt 3 (4 - 6 m up the stem), a gentle decline in stiffness was

observed to the top of the stem. Xu and Walker (2000), who tested MOE on 90 x 35 x 4200 mm boards and averaged the boards from within a log length (4.2 m long) to give a mean MOE for that log, observed that the butt log had the lowest MOE values, whilst the MOE values in the second log were the highest before decreasing up the stem. The height up the stem of the second log (4.2 - 8.4 m) which displayed the greatest MOE, corresponds well with results of the study reported here, however, bolt 2 (2 - 4 m up the stem) in this trial was found to exhibit a MOE value very similar to that of the stiffest bolt. This particular length was included in the butt log for Xu and Walker (2000) and subsequently their study missed whether this portion of the stem was in fact of high MOE. The vertical changes in MOE up the stem as noted by Xu and Walker (2000) displayed only an 8% difference between the weakest and stiffest logs, in which some of the accuracy would have undoubtedly been lost due to averaging, however, it was somewhat less than the 58% difference at the higher stockings and the 36% difference at lower stockings within this trial. Similarly, Tsehaye *et al.* (2000) found in their study of 3.6 metre logs from Canterbury, where the mean log MOE was derived from 90 x 35 mm dressed boards, that only a 6% difference existed between the weakest and stiffest logs, with the second log being the stiffest.

The discovery in this trial of low stiffness within the lowest portion of the stem confirms previous observations by Tsehaye (1995), Xu (2000) and Xu and Walker (2000). It is also a common feature found within other species, such as sugi trees (Hirakawa and Fujisawa, 1996) and Norway spruce (Perstorper, 1996). Xu (2000) stated that up to approximately three metres up the stem, stiffness was inferior to that in the stem above this point, whilst Xu and Walker (2000) found that the low stiffness was within the butt log, which extended 4.2 metres up the stem. This trial suggests that the area of low stiffness within the butt log might be confined to an even smaller distance up the stem, as the second bolt displayed MOE values almost identical to that of the stiffest bolt within this trial. This zone of poor MOE is probably a result of the large proportion of low stiffness corewood present within the butt log, which forms a truncated cone from the base of the tree to approximately three metres up the stem (Xu and Walker, 2000; Huang *et al.*, 2003; Xu *et al.*, 2004). This localised reduction in MOE has been suggested to serve a functional purpose (K. Niklas, pers. comm.). It has been suggested that the base of tree acts as a “hinge” to allow trees the ability to

sway when external forces are applied. Niklas speculated that the localised reduction in MOE was adaptive in terms of wind-induced bending moments which allow the trunk to bend in the wind. Furthermore, low MOE at the base that affects the structural integrity of the tree may be due to other functions that the stem is required to perform other than stability.

Within the study reported here, the height up the stem at which MOE was greatest increased as stocking decreased as demonstrated by the increase in MOE with proportional height. MOE reached its greatest value for individual trees in the trial reported here between 15% and 40% of stem height at stockings of 635 stems ha^{-1} and above, and between 25% and 50% of stem height at stockings of 481 stems ha^{-1} and below. As the mass and thus weight of trees higher up the stem is greater at lower stockings, the relative increase in MOE up the stem may be a response in order to support the extra weight of a thicker stem, larger branches and greater leaf area. This increase in MOE proportionally higher up the stem at lower stockings compared with higher stockings would have enabled the affected stems to handle the increased weight of the stem and therefore, reduce the possibility of elastic buckling. This may also be in response to the impact of external forces such as wind and snow. The increased "sail area" of a larger tree with a large stem covered in foliage may require increased stiffness to ensure that when these external forces are applied, a tree can structurally support itself from mid-stem mechanical failure.

It is surprising that MOE should be greatest some distance up the stem at any stocking, considering that the proportion of corewood increases dramatically with height up the stem and conventional analysis would expect a deterioration in log quality with height. The interpretation lies in the abnormally low stiffness of the corewood in the butt log being counterbalanced by very stiff outerwood, whereas at the top of the stem the corewood is somewhat stiffer, but there is only little outerwood of moderate stiffness (Tsehaye *et al.*, 2000).

Burdon *et al.* (2004) have suggested that in addition to having corewood and outerwood, a tree has different degrees of each. They suggest that corewood up the tree can be divided into juvenile corewood at the bottom, transitional corewood approximately three to five metres up the stem and mature corewood above it. The

same applies for outerwood. These results reported here would support such a concept. As several wood properties, which are known to be important, show pith to bark trajectories that vary markedly up the stem, such segregation has merit.

Megraw (1985) has stated that the concept of juvenile wood consisting of a cylindrical core from the bottom to the top of the tree is a useful concept, but that it is not biologically correct because juvenile wood changes somewhat up the tree, which is why Burdon *et al.* (2004) suggested their concept. A fundamental property influencing MOE is density, however this property is unlikely to provide an explanation why MOE exhibits a peak between 15% and 50% of stem height. Numerous observations (Cown and McConchie, 1982a, 1982b; Donaldson and Burdon, 1995; Tian *et al.*, 1995) have noted that density decreases with increasing height up the stem, particularly up to a height of approximately three metres. Tracheid length also impacts on MOE, particularly through its relationship with microfibril angle which has been found to be very strong (r^2=0.91 - 0.92) (Echols, 1955; Erickson and Arima, 1974). Tsehaye *et al.* (1995) and Tsehaye *et al.* (1997b) found that in *Pinus radiata* from Canterbury, the logs that yielded the stiffest lumber had the longest tracheids, which occurred at approximately 50% of tree height. Microfibril angle shows a rapid decline from the butt to a height of seven metres at rings of comparable cambial age, after which angles then remain more or less constant (Donaldson, 1992). The reduction of microfibril angle in the corewood higher up the stem has been suggested to be a result of physiological ageing of the cambium (Barnett and Bonham, 2004), however, the whole tree, not just a certain area, exhibits physiological ageing. Microfibril angle may contribute to the stiffest part of the tree being between 15% and 50% of stem height as Lindstrom *et al.* (2004) and Tsehaye *et al.* (1997a) found that decreasing microfibril angle was well correlated with increasing MOE (r^2=0.75; 0.83). Xu *et al.* (2004) strongly support the notion that microfibril angle is primarily responsible for low-stiffness wood in butt logs and an increasing MOE up the stem to a certain point.

As with the examination of outerwood MOE (Chapter 4), whole stem MOE of two metres bolts up the stem was found to show a greater correlation with slenderness than diameter. In previous studies and that of the outerwood MOE in this thesis, slenderness and diameter were assessed on a whole stem, often having just one

measurement of each for a tree. In this assessment of vertical MOE, slenderness and diameter were assessed every two metres up the stem and assessed to see if a correlation with MOE existed. As with previous observations (Watt *et al.*, 2006a), slenderness displayed a positive relationship with MOE and was found to be a substantially more important indicator of MOE than diameter.

Sawmillers are not primarily interested in obtaining significantly superior wood, but that as much of the wood supply as possible should meet some minimum threshold value for stability, stiffness and strength (Huang *et al.*, 2003). It is therefore necessary not to set about creating more trees with greater stiffness but to raise the level of the least stiff trees in a stand. As plantations in New Zealand continue to be harvested at ages younger than in the past, a higher percentage of corewood will exist in the resource, thus creating a lower quality and more variable wood resource for industry to process. Increased corewood content in sawlogs would mean that the proportion of lower grade lumber in the sawmilling industry increases in both absolute and relative terms (Lindstrom *et al.*, 2005). Sawn lumber with high proportions of corewood is known to have lower modulus of elasticity along with other undesirable properties such as substantial drying distortion. However, by incorporating genetics, plantation management, namely migrated through stand spacing, and improved log sorting using portable acoustic methods, this trial has shown that average whole stem MOE at stand level can be raised.

CONCLUSIONS

- Mean tree MOE displayed a 34% difference in MOE between 275 stems ha^{-1} and 2551 stems ha^{-1}, ranging from 5.18 GPa to 6.96 GPa.

- Gains in MOE occurred between different breeds. The 870 breed displayed an 8% and 16% gain in MOE over the 268 and 850 breeding series, respectively.

- The lowest portion of the stem (bolt 1) was approximately 30% less stiff than bolts 2 and 3 immediately above. After the maximum MOE was

obtained at bolt 3, a gentle decline in MOE occurred up to the top of the stem.

- Vertical variation in MOE was significant, with MOE for individual bolts exhibiting a 56% difference at stockings of 1457 stems ha^{-1} and above, with a 36% difference in MOE up the stem occurring at stockings of 635 stems ha^{-1} and below.

- The proportional height at which maximum MOE was obtained increased from between 15% and 40% at stockings of 635 stems ha^{-1} and greater to between 25% and 50% of stem height at stockings of 481 stems ha^{-1} and less.

Chapter 6

Determination of critical buckling height and critical MOE using measured wood properties in *Pinus radiata*

INTRODUCTION

The vertical stems of terrestrial plants must mechanically sustain their own weight against the influence of gravity. They also must be sufficiently stiff and strong to resist bending and avoid breaking when subjected to large externally applied mechanical forces (Niklas, 1993), thus MOE (also referred to as E) and density (ρ) are important mechanical properties. These properties are of interest because, in theory, the quotient of MOE and ρ (i.e. the density-specific stiffness, E/ρ) determines the extent to which vertical stems can grow before they reach their critical buckling height (i.e. the height at which elastic buckling is predicted to occur).

Recent research (Watt *et al.*, 2006a, 2006b), including that of this thesis, suggests that MOE may be regulated by stem slenderness. When light demanding species such as *Pinus radiata* are subject to competition from neighbouring plants, rapid height growth is important to ensure that they are not overtopped. Under high levels of competition trees become etiolated as priority is given to height growth at the expense of diameter increment. Based on Euler's buckling formula, the critical height (H_{crit}) that a vertical tree stem can reach before it undergoes elastic buckling is given by the following equation:

$$H_{crit} = C\left(\frac{E}{\rho}\right)^{1/3} D^{2/3} \qquad (1)$$

where C is the constant of proportionality, E is modulus of elasticity, ρ is the average wood density and D is stem diameter (Greenhill, 1881). For a given MOE actual height will approach the critical height as height for a given diameter, or stem slenderness, increases. In a recent study (Watt *et al.*, in prep) which used both examined mechanical and structural properties of 15-year-old buckled trees, equation 1 was found to provide a reasonable approximation of the buckling height.

The value for C can vary between 0.79 and 1.97 depending on assumptions about loading conditions and tree taper (Niklas, 1997). Regardless of the numerical value of C, however, equation 1 predicts that the scaling of H obtains the proportionality $H \propto D^{2/3}$, provided E/ρ and the safety factor remain constant. This assumption is the basis for the elastic similarity model proposed by McMahon (1973) and McMahon and Kronauer (1976) which predicts the scaling of tree height based on diameter (i.e. $H \propto D^{\alpha=2/3}$). However, if E/ρ is not a constant, then the scaling exponent α for the proportional relation $H \propto D^{\alpha}$ depends upon the scaling of E/ρ with D (Niklas, 1993). The testing of the assumption has typically been carried out at a very broad level, investigating variation between genera (Niklas, 1993) and between species (Niklas, 1994a). More recently, this assumption has been tested on four-year-old *Pinus radiata* across a wide environmental range (Watt *et al.*, 2006b), however, how it relates with mature *Pinus radiata* exhibiting a wide range of stem diameters and MOE is unknown.

For a given MOE, actual height will approach the critical height as stem slenderness (S) increases. Low slenderness ratios (H/D) indicate that very large self-loads are required to induce elastic buckling, whilst high slenderness ratios indicate that smaller self-loads are required to produce elastic buckling. These generalities exist because, for any columnar support member, the slenderness ratio is proportional to $(E/P)^{1/2}$, where E is the stiffness and P is the maximum self-load that a column can support, i.e. $H^3/D^2 \propto (E/P)^{1/2}$. Thus, the mechanical stability of very slender columnar stems requires either tissues with high stiffness or stems with low P (Niklas *et al.*, 2006). The Greenhill (1881) equation shows that trees can increase their critical height to avoid buckling as slenderness increases by increasing their density-specific stiffness (E/ρ), which is mainly accomplished through increases in MOE as green density is relatively constant (Watt *et al.*, 2006a).

Even though the height of a tree, H, may never exceed the critical buckling height, H_{crit}, the degree to which H approaches H_{crit} may influence wood properties. The safety factor is defined as the quotient of H_{crit} and H. If growth in size attains a safety factor less than unity, then the stem is predicted to elastically deform under its own weight. Safety factors greater than unity, therefore, indicate that an individual plant

can sustain greater mechanical loadings than those imposed by its own biomass (Niklas, 1994a). Rearrangement of equation 1 in terms of the safety factor (H_{crit}/H) as:

$$\frac{H_{crit}}{H} = \frac{C(E/\rho)^{1/3} D^{-1/3}}{S} \quad (2)$$

shows that for a given diameter, increases in slenderness need to be accompanied by increases in MOE to maintain a constant safety factor (Watt *et al.*, 2006b). Furthermore, using a variant of the Euler column formula, the MOE that a tree must obtain for a given height and diameter to ensure that elastic buckling is avoided can be calculated, where E is critical MOE:

$$E = \frac{\rho H^3}{C^3 D^2} \quad (3)$$

The objective of this study was to (i) use measured wood properties to assess critical buckling height for each felled tree, whilst using allometric analysis to examine relationships between H_{crit}, H, D, S and MOE, at the whole tree level; (ii) determine critical MOE for outerwood and compare with measured outerwood MOE obtained using a time of flight instrument at the whole tree level and (iii) determine critical MOE for each two metre bolt up the stem for the 72 felled trees at the bolt level, unless otherwise stated. Results are to be examined with particular focus on critical buckling height and theoretical critical MOE for outerwood and vertical bolts.

METHODS AND MATERIALS

Location

Measurements were taken from 17-year-old *Pinus radiata* trees that had been grown in a Nelder experiment (Nelder, 1962) located at Burnham, approximately 18 km south-west of Christchurch (latitude 43°36.5'S, longitude 172°17.75'E, altitude 70 m a.s.l.). They were situated on Lismore stony silt loam soil (N.Z.S.B., 1968) and experienced a mean annual precipitation of 650 mm, in which seasonal water deficits do occur during January to March, when evapotranspiration exceeds rainfall (G. Furniss, pers. comm.).

Experimental Plot

The experiment comprised five breed/cutting treatments, including seedlings from the 850, 870, and 268 breeding series and cuttings taken from one-year-old and three-year-old parents. Both the one and three-year-old cuttings were from the 268 series. The Nelder contained 45 spokes separated by 8 degree intervals in 10 circular rings (Figure 5.1) with high initial stocking rates present at the centre of the Nelder to low initial stocking rates present on the outer ring of the Nelder (Nelder, 1962) (Table 5.1). Each breed/cutting treatment occupied nine of the spokes split in a group of five spokes on one side of the plot and a group of four spokes on the other side of the plot. The trees had not received thinning at any stage prior to examination. Due to natural mortality, windthrow or malformation, 182 trees that had complete neighbours were suitable for examination. From this population, 72 trees were examined.

Measurements

Measurements of outerwood MOE were made on 385 *Pinus radiata* trees representing ten different initial stand spacings and five breed/cutting treatments using the time of flight instrument, TREETAP (Chapter 4).

Seventy-two *Pinus radiata* trees representing five different breed/cutting treatments and a range of initial stand spacings were then felled (Chapter 5). Three repetitions of each of the breed by spacing interactions were sought. All 72 stems were de-limbed and cut into two metre long bolts up the entire length of the stem (Table 6.1). Assessment of wood velocity for all two metre bolts (n=543) from the 72 felled trees was carried out using HITMAN, an acoustic resonance instrument, which provided a volume weighted average of velocity (Harris and Andrews, 1999).

Table 6.1. Bolt number and corresponding (m) height up the stem.

Bolt 1	Bolt 2	Bolt 3	Bolt 4	Bolt 5	Bolt 6	Bolt 7	Bolt 8
0-2	2-4	4-6	6-8	8-10	10-12	12-14	14-16

Green density was calculated from a sample of 38 discs taken at 1.4 metres above ground level. At time of felling 30mm discs were taken for the 38 trees. Green density

was determined as green weight/green volume using the immersion technique. From analyses of these measurements, green density was found to vary with neither breed nor stocking and mean density was 935 kg m^{-3} (± 8.2 kg m^{-3}).

Data analysis

Critical height was determined using equation 1, where a value for *C* of 0.792 was used, which assumes that the applied force to the tree stem is distributed over the full extent of the tree (Greenhill, 1881). For dimensional consistency, equation 1, requires that density-specific stiffness be expressed in units of m, by converting the value of ρ which was 935 kg m^{-3} into Newton m^{-3} (i.e. 1 kg weight force = 9.8067 N).

Regression models of the form

$$\log Y = \log\beta + \alpha \log X$$

were used to determine the parameters α and β for the allometric relationships defined as log*Y* and log*X* (Watt *et al.*, 2006b). Reduced major axis regression (RMA) analyses were used to determine the scaling exponents and allometric constants (i.e. α_{RMA} and $\log\beta_{RMA}$, respectively) for the log*Y* vs. log*X* allometric trends observed. RMA was used as the objective of the regression analysis was to determine functional rather than predictive relationships between two biological variables (Niklas *et al.*, 2006). The regression parameters were computed using the formulae $\alpha_{RMA} = \alpha_{OLS}/r$ and $\log\beta_{RMA} = \overline{\log Y} - \alpha_{RMA}\ \overline{\log X}$, where α_{OLS} is the ordinary least squares (OLS) regression exponent, *r* is the OLS correlation coefficient and $\overline{\log Y}$ and $\overline{\log X}$ denote the mean values of variables log*Y* and log*X* (Niklas, 1994b; Watt *et al.*, 2006b). The 95% confidence intervals (CI) for α_{RMA} and $\log\beta_{RMA}$ were determined using the formulae 95% CI = $\alpha_{RMA} \pm t_{N-2}\ (MSE/SS_X)^{1/2}$ and 95% CI = $\log\beta_{RMA} \pm t_{N-2}\ \{MSE[(1/n) + (\log X^2/SS_X)]\}^{1/2}$, where t_{N-2} is the t value, *MSE* is the OLS regression model mean square error, SS_X is the OLS sums of squares and *n* is the sample size (Niklas, 1994b; Watt *et al.*, 2006b).

Critical MOE, which is the MOE that a tree must obtain for a given height and diameter to ensure that elastic buckling is avoided, was calculated for both outerwood and vertical bolts. Critical MOE for the vertical bolts was determined using the diameter of the bolt at the midpoint of the stem section and the height of the stem above the midpoint of the bolt. As well as assessing comparative differences between critical MOE and actual MOE, critical MOE as a predictor of actual MOE was examined.

RESULTS

Critical height and allometric scaling relationships

Critical buckling height for the 72 trees assessed showed that actual height (H) was below that of critical height (H_{crit}) (Figure 6.1). Only one tree at the highest stand stocking was deemed to be especially close to unity ($H = H_{crit}$). This was due to the very low stem diameter that the tree displayed. This low diameter combined with the relative height of the tree meant that stem slenderness was high, considerably more than any other tree.

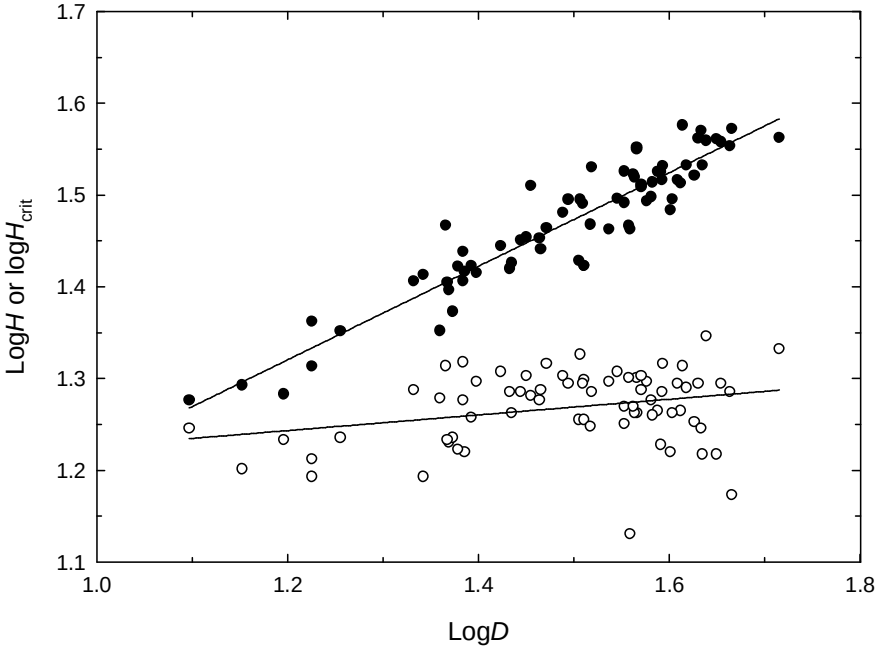

Figure 6.1. Log-log (base 10) plot of ground line diameter against actual height (white circles) and estimated critical buckling height (black circles).

Regression of critical buckling height against diameter (Figure 6.1) yielded a scaling exponent of 0.55, which was lower than the scaling exponent of 0.67 predicted with constant E/ρ by equation 1, as $(E/\rho)^{1/3}$ scaled with D to the power of -0.25. The scaling exponent between actual height, H, and D was 0.30. MOE scaled negatively with stem diameter to the power of -0.75, but positively with stem slenderness to the power of 0.78 (Table 6.2).

Table 6.2. Summary statistics of reduced major axis (RMA) regression of log*Y* vs. log *X*.

log*Y*	log*X*	α_{RMA}	$\log\beta_{RMA}$	r^2
*H*crit	*D*	0.55 (0.45 - 0.64)	0.66 (0.21 - 1.10)	0.87
H	*D*	0.30 (0.07 - 0.53)	0.81 (0.30 - 1.33)	0.08
$(E/p)^{1/3}$	*D*	-0.25 (-0.44 - -0.06)	2.28 (1.10 - 3.46)	0.39
MOE	*S*	0.78 (0.60 - 0.96)	-0.69 (-1.07 - -0.32)	0.42
MOE	*D*	-0.75 (-0.93 - -0.56)	1.81 (1.45 - 2.16)	0.39

The scaling exponent (α_{RMA}) and allometric constant ($\log\beta_{RMA}$) are presented with 95% confidence intervals in parentheses.

Trees with greater slenderness ratios displayed lower safety factors than trees with lower slenderness. The measurements showed that the average safety margin (H_{crit}/H) of the trees in this study was 1.60, in which only five of the 72 trees had a safety margin greater than 2 (i.e., H_{crit} was double that of H). The safety factor ranged from 1.07 to 2.50 and increased with increasing diameter and decreasing stem slenderness. The regression of $\log(H_{crit}/H)$ against log$D$ indicated that the safety factor was moderately correlated with stem diameter (r^2=0.39). Stem slenderness and the safety factor were highly correlated (r^2=0.79), with an exponential regression curve providing the best fit for the data (Figure 6.2).

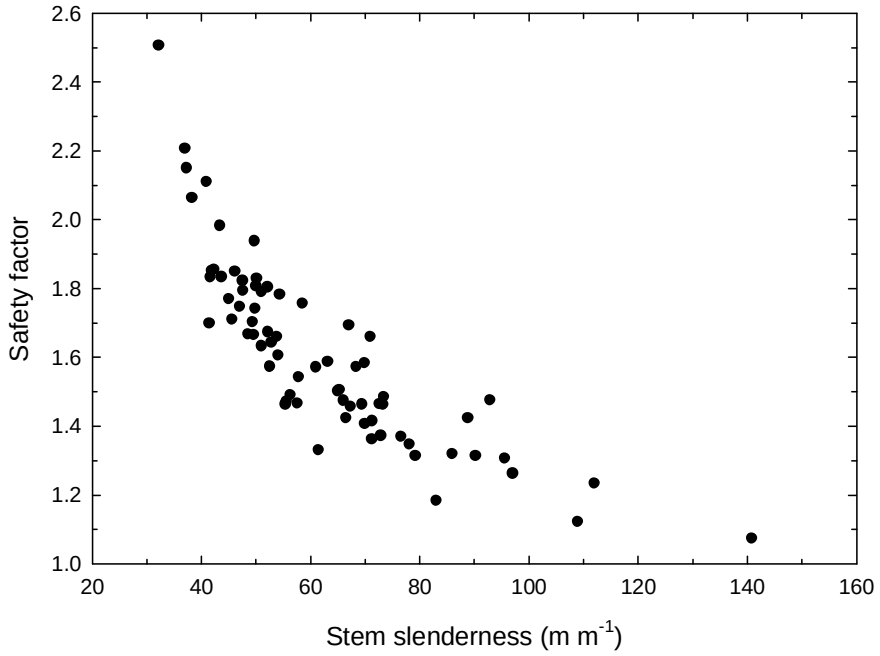

Figure 6.2. Relationship between the safety factor (H_{crit}/H) and stem slenderness (H/D).

Critical MOE

The assessment of critical MOE for outerwood found that all but one of the 385 trees had an actual MOE at breast height (1.4 m above the ground) above the theoretical MOE required for the given diameter and height of any tree to ensure elastic buckling was avoided (Figure 6.3). As a predictor of actual MOE, critical MOE was significant (P<0.0001), but only accounted for a low proportion (r^2=0.29) of the variation in measured MOE. Critical MOE explained a slightly greater proportion of the variation in measured MOE than was explained by stem diameter (r^2=0.28) at the tree level, though it was less than was explained by stem slenderness (r^2=0.33) at the tree level.

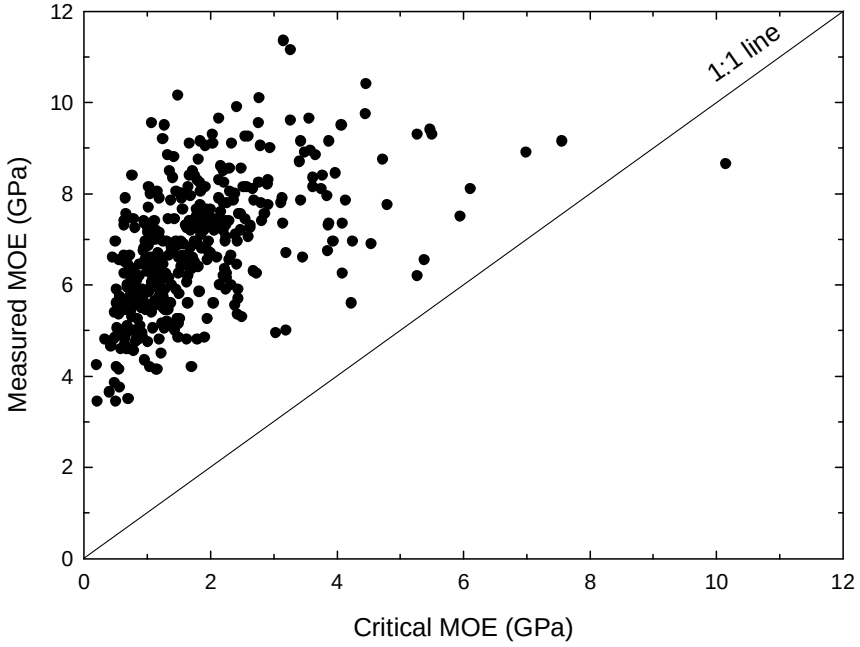

Figure 6.3. Plot of measured outerwood MOE against critical outerwood MOE.

The examination of critical MOE for each individual vertical bolt revealed that all vertical bolts from the 72 felled stems were above the estimated critical MOE (Figure 6.4). The mean diameter and height of the stem above the middle of any bolt was used to assess what the theoretical MOE required was to ensure that elastic buckling did not occur at that point of the stem. When assessing bolt MOE, critical MOE displayed greater correlation (r^2=0.22) with measured MOE than diameter (r^2=0.03), however, it was not as strong as the correlation shown by bolt slenderness (r^2=0.24).

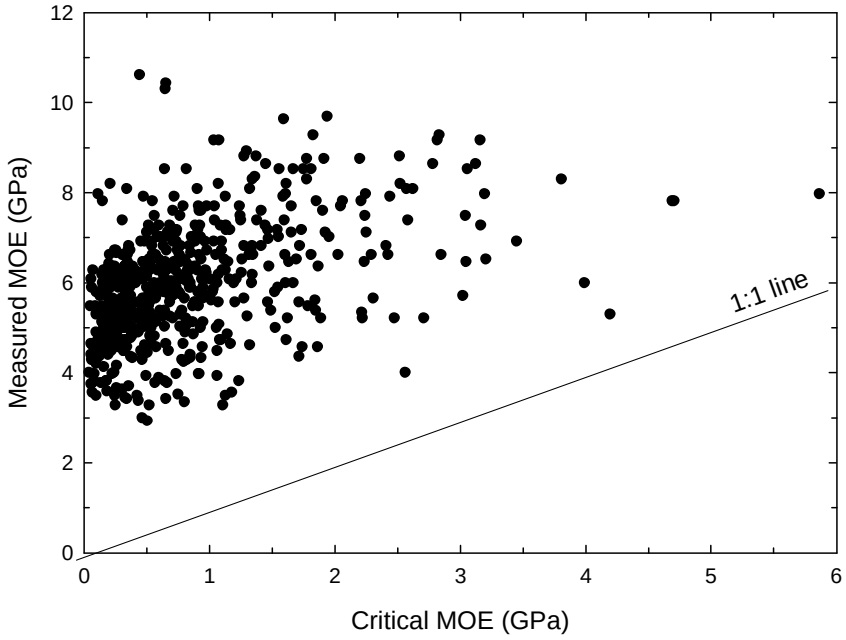

Figure 6.4. Plot of measured vertical bolt MOE against critical vertical bolt MOE.

Whilst actual MOE was low at the base, followed by an abrupt rise in MOE, critical MOE rarely displayed such a pattern for the 72 trees examined (Figure 6.5). Variation in critical MOE within any one stem was also less than that demonstrated by actual MOE and typically exhibited less abrupt fluctuations in MOE at any point up the stem.

A noticeable trend to arise out of the assessment of critical bolt MOE was that there was a clear tendency for some bolts with lower mean diameter to have greater safety margins; that is the actual MOE was substantial greater than the theoretical critical MOE (Figure 6.6).

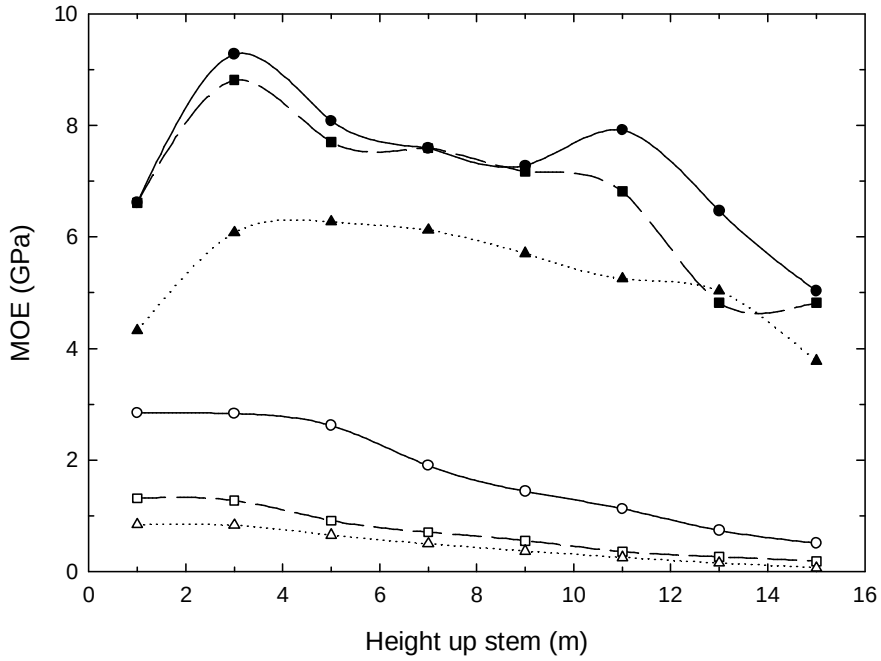

Figure 6.5. Plot demonstrating disparity between actual MOE (black shapes) and critical MOE (white shapes) up the stem of three trees (actual MOE and critical MOE for each tree have same shape) at 2551 stems ha^{-1} (solid line), 1457 stems ha^{-1} (long dash) and 635 stems ha^{-1} (dots).

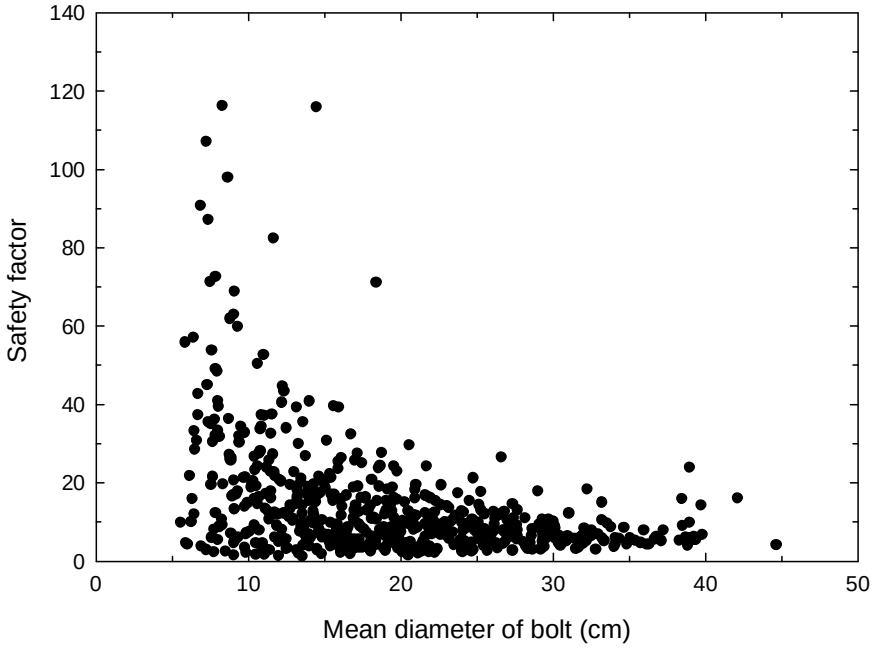

Figure 6.6. Relationship between safety factor (MOE/critical MOE) and mean diameter of all measured bolts.

DISCUSSION

The examination of critical buckling height revealed that none of the trees were above the theoretical point of buckling. Only trees at the highest stand stocking were expected to be close to the buckling point, with a single tree especially close to unity. As tree height was relatively similar within the trial, increasing stem diameter, thus decreasing stem slenderness resulted in increased safety margins.

The scaling exponent between critical height and diameter at ground level was lower than predicted (0.55 vs. 0.67) and more closely resembles the stress similarity model ($\alpha = 0.50$), contradicting the assertion that trees obtain elastic similarity ($H \propto D^{2/3}$). This exponent is not consistent with findings of Watt *et al.* (2006b) who observed a scaling exponent of 0.95 in four-year-old *Pinus radiata*. Such differences in scaling exponents between trials can be explained by previous research from Whittaker and Woodwell (1968), who found that young trees have a higher scaling exponent between height and diameter than mature trees. The scaling exponents of critical and actual height resulted in a divergence between these two variables with increasing stem diameter. A greater amount of the variation in MOE was attributable to stem slenderness (r^2=0.42) than diameter (r^2=0.39).

Safety margins (H_{crit}/H) increased with increasing diameter at ground level. This violated the assumption of constant safety margins which form the basis of the elastic similarity model. The scaling exponent of 0.30 between actual height and diameter observed in this trial was substantially lower than the scaling exponent ($\alpha = 0.67$) as predicted by the elastic similarity model. This low scaling exponent between height and diameter at ground level occurred as the low variation in height was accompanied by a higher variation in diameter across the site. The scaling exponent is very different from that observed by Watt *et al.* (2006b) who found that the safety margin declined with increasing diameter at ground level ($\alpha = 1.63$). Such differences may be explained by between site variations or age differences in the material examined.

The safety factor was above unity for all trees and was only very close to unity for one tree at the highest stand stocking (2551 stems ha^{-1}). Assuming the value of density-specific stiffness measured at the base of a tree is representative of the whole

stem, our measurements show that the average safety margin of the trees in this study was 1.60 with a range of 1.07 to 2.50. These values are similar to those reported for nine-year-old sweet gum (Holbrook and Putz, 1989) and those of four-year-old *Pinus radiata* (Watt *et al.*, 2006b) growing under competition. Significantly higher safety factors (4 - 5) compared to that reported here have been suggested in the literature (McMahon, 1973; McMahon and Kronauer, 1976; Niklas, 1993, 1994b). The safety margin improved with increasing diameter and decreasing stem slenderness. The relatively low safety margins found in this study are likely to be attributable to the higher stocking rates indicative of plantation grown trees, which induces a more unstable etiolated form than occurs in open grown trees.

These results in conjunction with Watt *et al.* (2006b) suggest reductions in the safety factor, associated with increases in slenderness, induced increases in MOE to reduce the risk of stem buckling. In this trial, diameter was found to be negatively correlated with MOE, whilst slenderness was positively correlated. Watt *et al.* (2006a) found in four-year-old *Pinus radiata* that diameter and slenderness were both positively correlated with MOE. This similarity in the relationship between slenderness and diameter suggests that slenderness might have been a causal variable rather than a response variable, and that the effects of diameter on MOE were mediated through slenderness.

The relationship found between MOE and stem slenderness in this trial has a sound theoretical basis. Using a variant of the Euler buckling formula, Greenhill (1881) showed that MOE scaled positively with the maximum slenderness that can be attained before buckling occurs. It therefore suggests that trees with high slenderness are increasing MOE to further increase the threshold at which buckling occurs. The strong relationship between slenderness and safety factor was not surprising as slenderness is the dominant term in equation 2.

The Euler formula must be viewed as a pedagogical tool that offers insights into the relations among variables that are much more complex in most real biological contexts. The formula assumes that columns are perfectly straight and uniform in cross-section; that the column must be constructed from an isotropic material, i.e. it must have a uniform MOE throughout; and that the weight of the column must be

significantly less than the weight it supports, i.e. the column is essentially considered to be weightless. Clearly, stems are rarely if ever ideal columns. They typically taper, lack a uniform MOE, and they are anything but weightless (Niklas, 1992). Even so, the Euler column formula provides a handy tool for examining relationships between biological variables.

Bolts with greater diameter were identified as more likely to have lower safety margins than bolts with lower diameters. This suggests that points where the diameter is greatest (i.e. at the base of a tree) are the most likely places for elastic failure to occur. This would reinforce statements made in Chapter 5 that the base of a tree is an area of concern, not only for potential lost earnings arising from low stiffness wood located in the base, but also as a point most vulnerable to failure when external forces such as wind and snow are applied. It has been suggested (K. Niklas, pers. comm.) that the base of a tree acts as a "hinge" to allow trees the ability to sway when external forces are applied. Niklas speculated that the localised reduction in MOE was adaptive in terms of wind-induced bending moments which allow the trunk to bend. This may be why the lowest bolts in this trial were so comparatively weak compared with bolts immediately above and why they were most likely to be susceptible to failure. Furthermore, this low MOE at the base that affects the structural integrity of the tree may be due to other functions that the stem is required to perform other than stability.

CONCLUSIONS

- The scaling exponent for $H \propto D$ was $\alpha = 0.30$, therefore the relationship did not comply with the elastic similarity model.

- The relationship between stem slenderness and MOE was significant and suggested that stem slenderness may be an important factor in stiffness development. Allometric scaling determined that slenderness (r^2=0.42) showed greater correlation with MOE than diameter (r^2=0.39).

- The safety margin ranged from 1.07 to 2.50, with an average safety factor of 1.60.

- Bolts with lower mean diameter often had greater safety margins, demonstrating that larger diameter bolts are the points of most likely elastic failure.

Chapter 7

Concluding remarks

This thesis examined the influence of initial stand spacing and breed on the stem geometry, outerwood MOE and vertical distribution of MOE of 17-year-old *Pinus radiata*. The dynamic modulus of elasticity of outerwood and two metre bolts up the stem were scrutinized and related to initial stand spacing and breed. Using measured mechanical properties of the trees, critical buckling height and allometric scaling relationships were also examined. Critical MOE as a predictor of actual MOE for outerwood and vertical bolts was assessed. An experimental plot was used that incorporated five breed/cutting treatments (850, 870, 268, three-year-old cuttings and one-year-old cuttings). The plot integrated ten levels of initial stand spacing ranging from 209 to 2551 stems ha^{-1}.

Stem geometry

Initial stand spacing had very pronounced influences on the physical characteristics of the trees assessed (Chapter 3). Stem diameter, crown height and stem slenderness were all highly correlated with spacing. Tree height was not affected by spacing or breed. Breed had a marginally significant influence on diameter and stem slenderness. Branch index was highly correlated with stem diameter and showed marked differences between breeds, in which 80% of the variation in branch diameter was explained. Spacing had little apparent impact on internode length, whereas, breed had a substantial influence on it. The long internode breed, the 870 series, displayed significantly longer internode lengths than the other breed/cutting treatments. After correction had been made for tree diameter, BIX exhibited a significant positive relationship with mean internode length which when included in the model increased the r^2 from 0.80 to 0.90. Tree diameter and mean internode length accounted for the effects of spacing and breed on BIX.

Influence of initial stand spacing and breed on MOE

The main body of this thesis was the examination of the influence that initial stand spacing and breed had on MOE (Chapters 4 and 5). When analysing outerwood MOE (Chapter 4), MOE was found to scale positively with stand spacing. The effect of propagation method on MOE showed that physiologically aged cuttings displayed improved MOE over seedlings, with cuttings of greater maturation status exhibiting higher MOE values. Relative gains in MOE between the highest and lowest stand spacings was 39%, in which the majority of this increase (33%) occurred with increasing stocking between 209 and 835 stems ha^{-1}. The gains in MOE attributable to breed were lower, however substantial differences existed between the five breed/cutting treatments. The three-year-old cuttings were stiffer than the one-year-old cuttings, seedlings from the 870, 268 and 850 breeds by 15, 17, 22 and 27%, respectively. Stem slenderness and green crown height were found to have direct influences on MOE, explaining 53% of the variance in MOE. The breeding series used within this study were not bred for improved wood properties such as stiffness, and as such, the examination of high stiffness material at a range of stand spacings as those used in this trial would have been most interesting.

The assessment of MOE using a resonance tool (Chapter 5) also found that MOE scaled positively with stand spacing. An examination of bolt MOE found that the lowest two metres of the tree were significantly weaker than the bolts immediately above. Bolts two and three were approximately 30% stiffer than bolt one. After MOE had reached its maximum up the stem at approximately bolt three, a gentle decline in MOE occurred to the top of the stem. Stand spacing significant (P<0.0001) influenced MOE up the stem. A peaked trend of MOE was evident at 1457 and 2551 stems ha^{-1}, however, this became more of a plateauing trend with decreasing stocking. The variation in MOE within trees was considerable (58%) at higher stockings, but less pronounced (36%) at 635 stems ha^{-1} and below. Bolt slenderness was the significant factor impacting on the MOE of individual bolts.

Critical buckling height and critical MOE

Chapter 6 examined the critical buckling height and allometric scaling relationships for the destructively sampled trees. Regression of critical buckling height against diameter yielded a scaling exponent of 0.55, which was lower than the scaling exponent of 0.67 predicted with constant density-specific stiffness. The relationship between stem slenderness and MOE was significant suggesting that stem slenderness may be an important factor in stiffness development.

Areas that further research could examine

Whilst the impact that spacing has on MOE has been clearly demonstrated in this study, the examination of high stiffness clones over comparative stockings would be most interesting and provide added valuable information.

As the region in which this trial was located has been identified as one of the poorest regions in New Zealand for the growth of plantation forests, the examination of MOE in mature trees across a range of sites would be most beneficial. The differences in MOE over a range of stockings at sites of greater quality may be even greater than those found within this study.

Whilst this study may have touched on management implications for MOE, further research is required in order to better understand mechanisms for MOE development and how they are related to management decisions. Research examining the following topics is recommended:

a) Determine the influence of tree sway on MOE.
b) Determine the influence of weed control and soil nutrition on wood properties, including MOE.
c) Determine the impact that green canopy has on MOE.
d) The examination of wood properties including tracheid length and microfibril angle up the stem at different spacings.
e) Assessment of the outerwood up the stem over a number of years to assess MOE development.

f) An economic evaluation of how changes in stand spacing and thus MOE impact stand value.

g) The development of a ring level model of stiffness.

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